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Laser Propulsion consists of using energy from a remotely located laser to heat a low molecular weight gas to extremely high temperatures then expand the gas through a nozzle to provide thrust. Because of the potential for significantly higher specific impulse than chemical propulsion and adequate thrust to provide reasonable transit times, laser propulsion can be considered for a wide range of mission applications. This report is an overview of the status of Continuous Laser Propulsion and is based on the AFOSR Laser Propulsion Workshop held at the University of Illinois on 8-10 February 1988.

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Proceedings

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Workshop On

LASER PROPULSION

8-10 February 1988

Mitat A. Birkan

AFOSR/NA

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LASER PROPULSION:

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ABSTRACT

Laser Propulsion consists of using energy from a remotely located laser to heat a low molecular weight gas to extremely high temperatures then expand the gas through a nozzle to provide thrust. Because of the potential for significantly higher specific impulse than chemical propulsion and adequate thrust to provide reasonable transit times, laser propulsion can be considered for a wide range of mission applications. This article is an overview of the status of Continuous Laser Propulsion and is based on the AFOSR Laser Propulsion Workshop held at the University of Illinois on 8-10 February 1988 and review of recent literature. It describes some of the challenges and opportunities for close collaboration among of fluid mechanics, optics and plasma physics basic research areas.

1. INTRODUCTION

The ability to perform ambitious space operations is strongly linked with heavier payloads requiring higher specific impulse propulsion systems. Laser propulsion offers the potential for a 3 fold increase in specific impulse over chemical rockets with adequate thrust to provide reasonable transit times[1]. A major advantage of laser propulsion is the combination of high thrust and high specific impulse without the need for a heavy onboard power source. In Figure 1, Laser propulsion is compared with chemical and ion propulsion as well as potential advanced concepts including solar, magnetoplasmadynamic (MPD), nuclear and hybrid plume. Thrust density is defined as the force per unit area of nozzle exit. This allows comparison of several propulsion systems with different nozzle sizes. Payload fraction can be expressed as[2],

$$\frac{\text{Payload Mass}}{\text{Total Initial Mass}} = \exp\left(-\frac{\Delta v}{g\, I_{sp}}\right) \qquad (1)$$

where Δv is the velocity increment required for the specified orbit transfer (6000 m/s for Low earth orbit to geosynchronous Earth orbit). The parameter g is the gravitation constant (~10 m/s) and the specific impulse, I_{sp}, of a rocket type thruster is defined as,

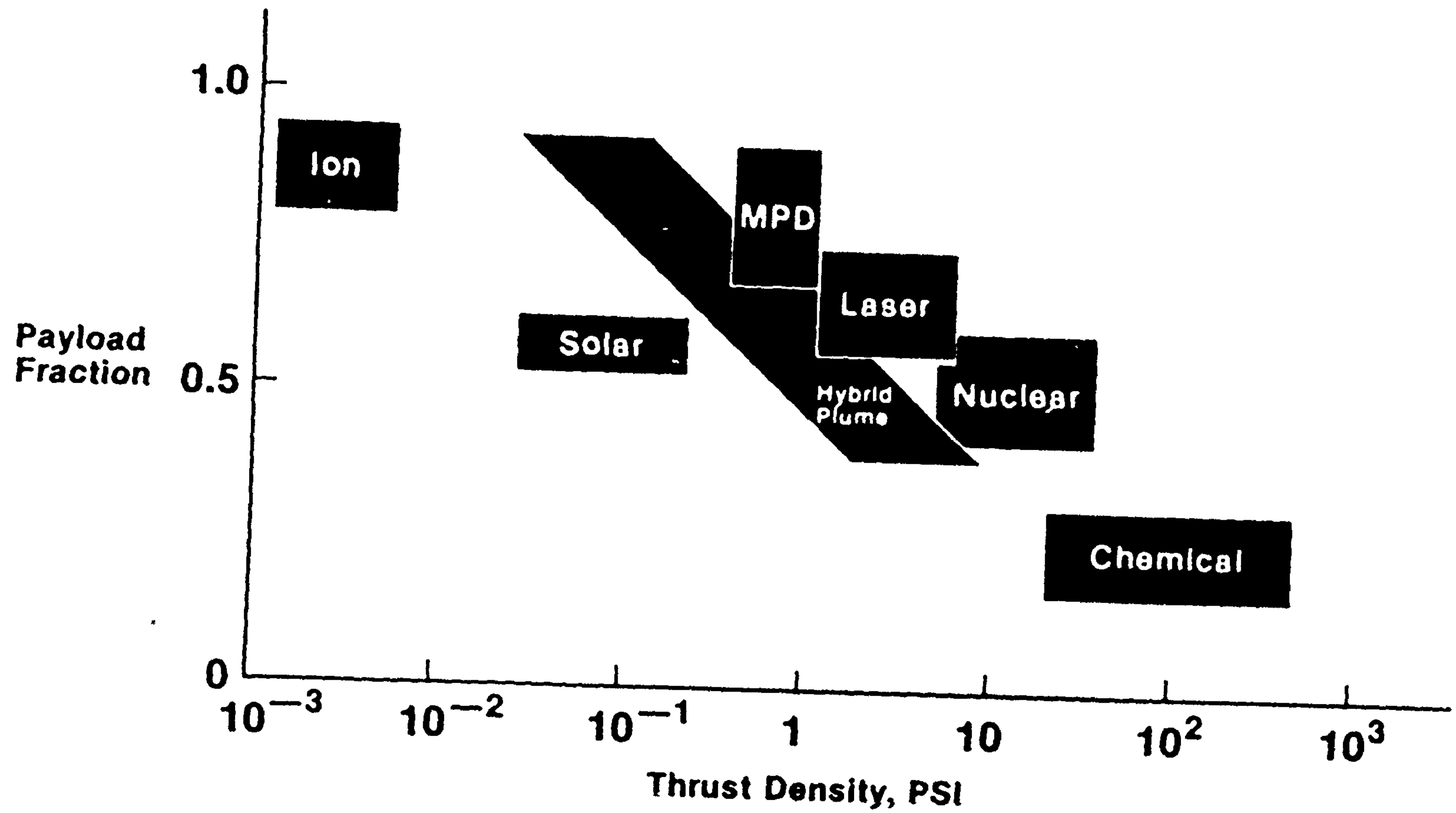

Payload
Fraction
1.0
0.5
0
Ion
Solar
MPD
Laser
Hybrid
Plume
Nuclear
Chemical
10−3
10−2
10−1
1
10
102
103
Thrust Density, PSI

FIGURE 1

$$I_{sp} = \frac{u_{ex}}{g} \quad (2)$$

u_{ex} is the average velocity of the exhaust propellant. For each system seen in Figure 1, the optimum specific impulse was used in Equation 1 rather than the theoretical limit. The optimum specific impulse for the laser propulsion system was chosen to be 2000 s because frozen flow losses become significant above this value[3]. By contrast, the optimum specific impulse for an electric propulsion system which must carry its own power (ion, MPD, and hybrid plume) depends upon the relative masses of the propellant and power supply as seen in Figure 2 [2]. The ratio of power source mass to the initial mass can be written as

$$\frac{\text{Power Source Mass}}{\text{Total Initial Mass}} = \beta_{ts} \Delta v\, g\, I_{sp}/t \quad (3)$$

where t is the trip time which can be approximated as[4],

$$t \cong \frac{\text{Total Initial Mass} \times \Delta v}{\text{Thrust}} \quad (4)$$

β_{ts} is the combined power matching and thruster efficiency. Hence power source weight is linearly proportional to the specific impulse. It should be noted that the propellant mass fraction which is propellant mass fraction=1-payload fraction is also shown on the same figure. The intersection of two curves determines the optimum specific impulse for a particular

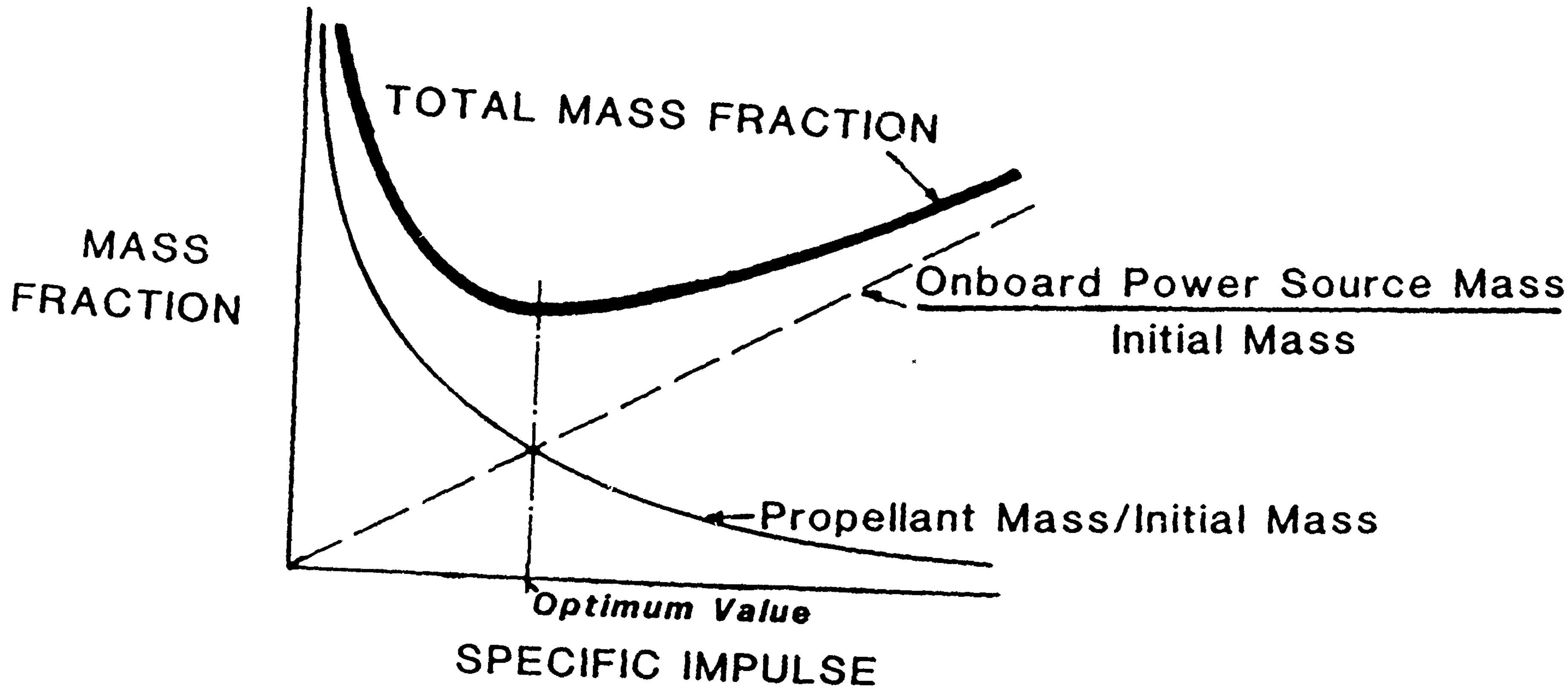

TOTAL MASS FRACTION
MASS FRACTION
Onboard Power Source Mass
Initial Mass
Propellant Mass/Initial Mass
Optimum Value
SPECIFIC IMPULSE

FIGURE 2

propulsion system.

Major components of a typical continuous laser propulsion system are seen in Figure 3 [5]. The laser source can be either on the earth or in space. A terrestrial laser source has easier access to electrical power and the weight of the system is less important. However, an earth based laser beam must be transmitted through the atmosphere which could obscure the beam. Although it eliminates the problem of atmospheric transmission, a space-based laser requires a massive power source in orbit. Future space-borne lasers are assumed to be solar or nuclear powered[6,7]; however, the major cost of these systems is the earth-to-orbit launch costs. The laser beam is collected and concentrated by a system of mirrors, then enters the absorption chamber through a window, and is absorbed by the propellant. After heating, the propellant exits via a nozzle, producing thrust[8].

Continous laser propulsion uses a steady state (or quasi-steady) plasma to absorb the energy of a laser beam through inverse bremsstrahlung to heat a propellant gas to exteremely high temperatures (15000 to 20000 K)[9]. If the working gas is hydrogen, a specific impulse of 1000 to 2000 seconds can easily be obtained[5,10]. Temperatures in the center of the hydrogen plasma can exceed 15000 K, and if the plasma were allowed to fill the entire absorption chamber, heat losses through the chamber walls

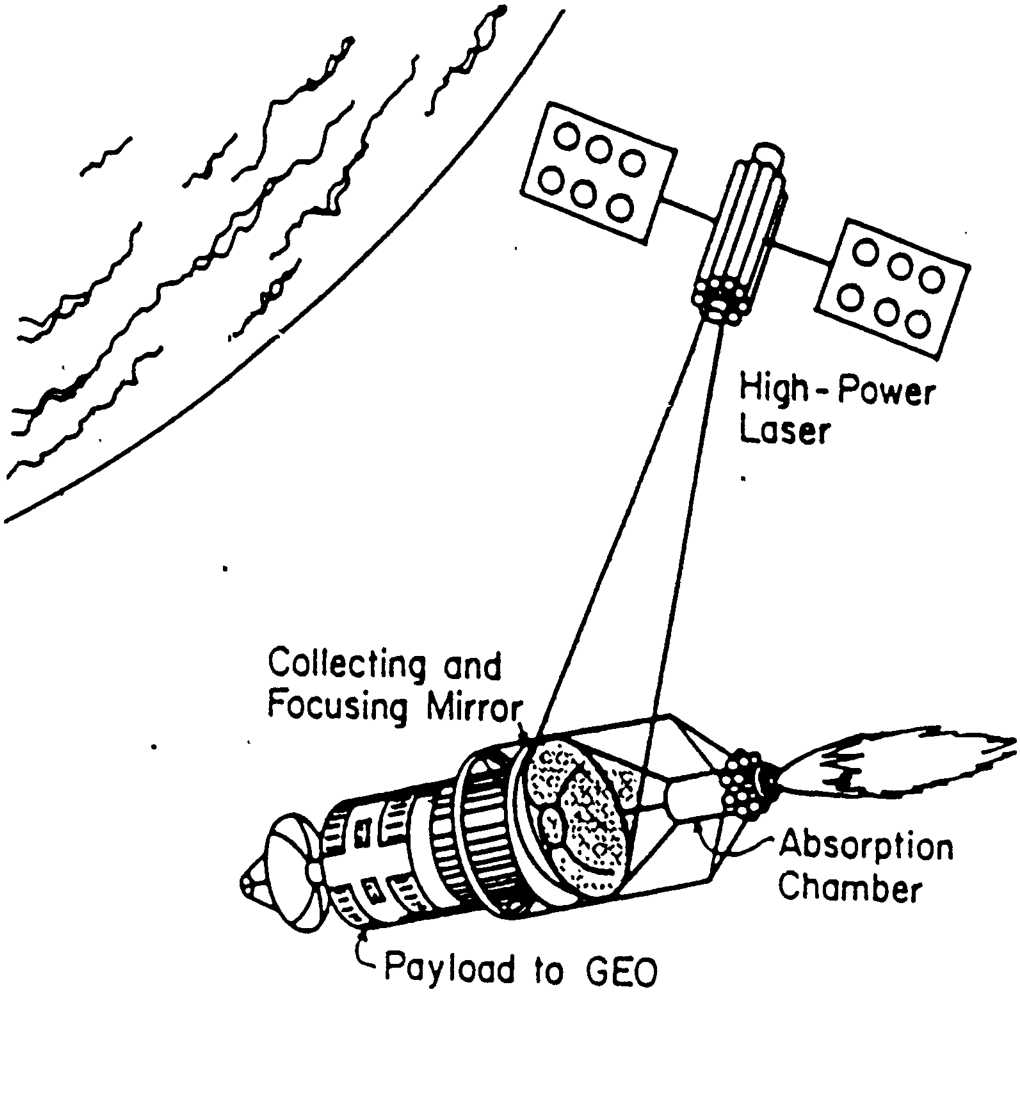

High - Power
Laser
Collecting and
Focusing Mirror
Absorption
Chamber
Payload to GEO

FIGURE 3

would be enormous and damage likely. The preferred approach is to use a dual-flow arrangement[8,10], as shown in Figure 4 [11]. In this concept a plasma is maintained in the central core of the chamber and an annulus of cold hydrogen flows around the plasma, isolating it from the walls. Downstream from the plasma is the mixing region where the hot and cold flows combine to give a uniform temperature at the entrance to the throat. The main reason for the two flows is to minimize heat losses to the chamber walls. The cold flow is designed both to prevent the plasma from contacting the walls and to absorb some of the radiation given off by the plasma. Heat loss is considered to be a major problem, and large devices could lose nearly half of the incident laser energy to the walls.

In addition to continuous laser propulsion there exists two related propulsion schemes which will not be covered in detail in this paper. They are double-pulse laser propulsion and microwave propulsion. Double-pulse laser propulsion[12], uses a transient detonation wave to provide thrust. A surface layer of solid propellant is vaporized by a low-power pulse which is followed by a larger main pulse that heats the vaporized fuel by inverse bremsstrahlung absorption. Thrust is generated using the expansion of the exhaust against the flat base of the launch vehicle as shown in Figure 5 [13]. Pulsed detonation wave propulsion has been considered for earth-to-orbit launch systems

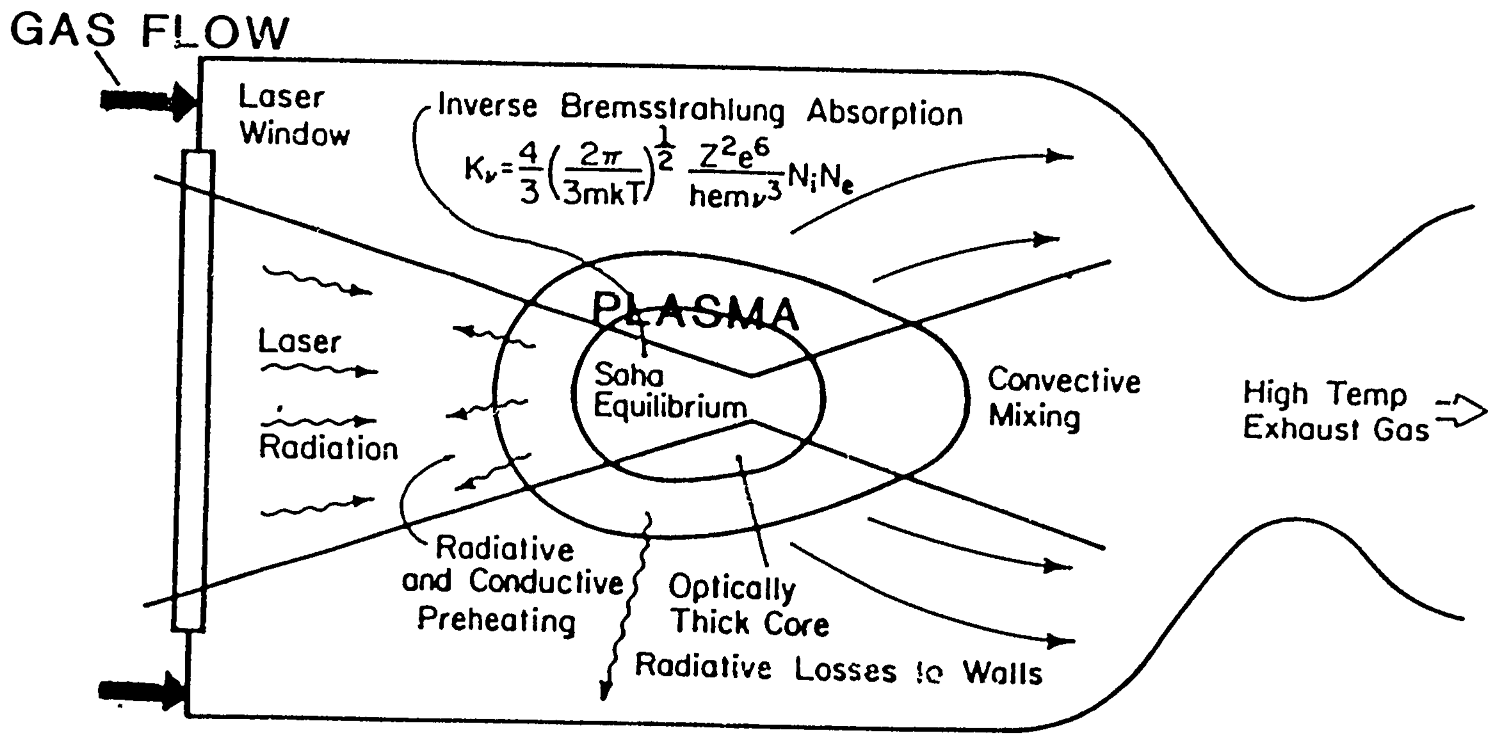

GAS FLOW
Laser Window
Inverse Bremsstrahlung Absorption
$K_\nu = \frac{4}{3}\left(\frac{2\pi}{3mkT}\right)^{\frac{1}{2}} \frac{Z^2 e^6}{hem\nu^3} N_i N_e$
Laser
Radiation
PLASMA
Saha Equilibrium
Convective Mixing
High Temp Exhaust Gas
Radiative and Conductive Preheating
Optically Thick Core
Radiative Losses to Walls

FIGURE 4

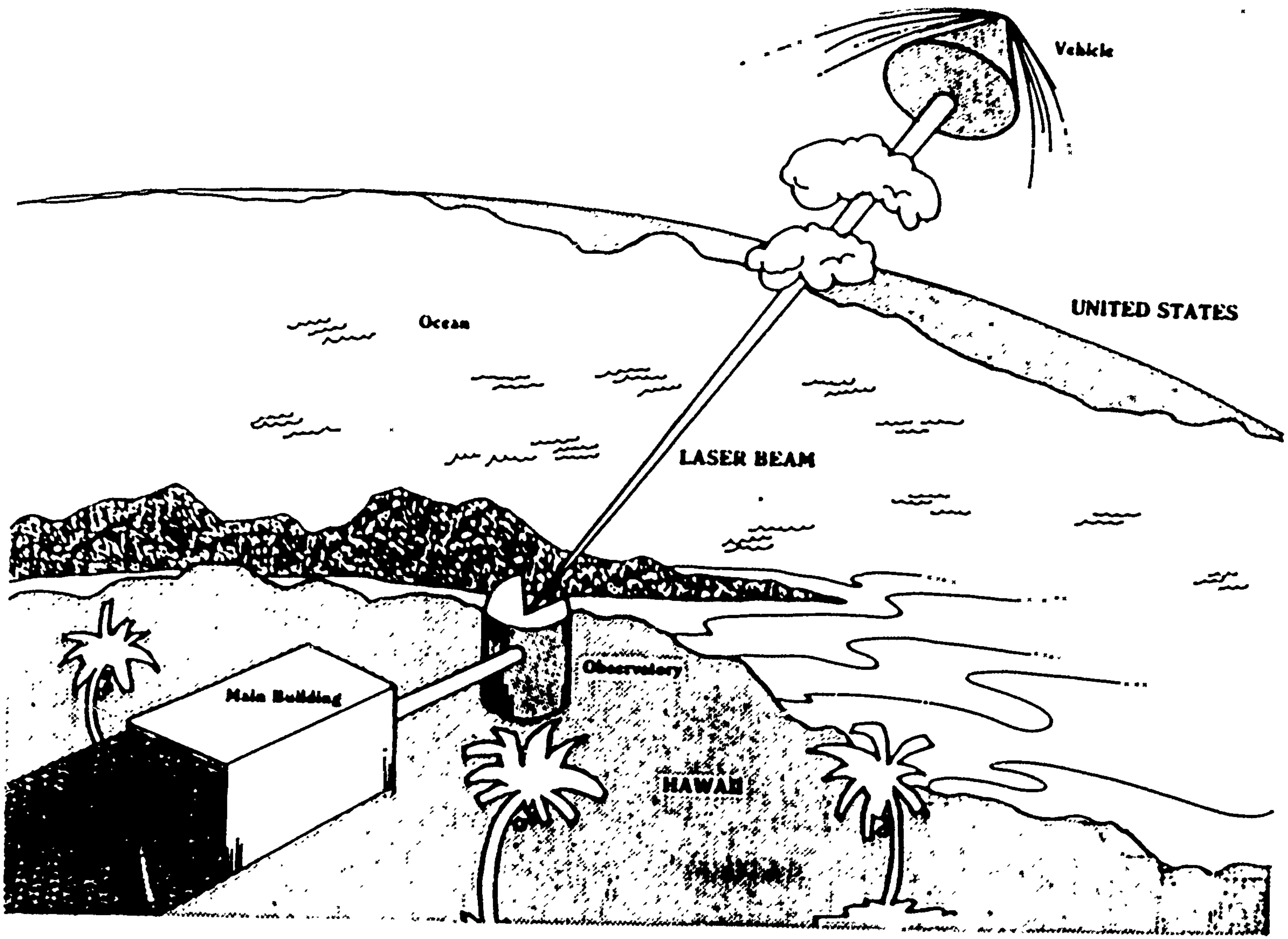

Vehicle
UNITED STATES
Ocean
LASER BEAM
Observatory
Main Building
HAWAII

FIGURE 5

and a specific impulse of 800 s and 40% energy efficiency are anticipated[14]. The characteristic laser power required is 1 GW or larger to launch useful payloads from Earth and the flux required to efficiently start a laser supported detonation wave is approximately $2x10^7$ W/cm^2 at 10 micron and increases roughly linear with laser frequency[14].

Microwave propulsion is an alternative continuous beam propulsion system. The microwave energy is absorbed by a gas in a microwave guide, a resonant cavity[15,16-20], a coaxial microwave plasmatron[21], or a plasma "flame front" region similar to a combustion wave[22-24]. Although one can generate microwaves with high efficiency (up to 85% [25]) and high absorptivity (up to 99.5% [15]), beamed microwave energy is limited to short generator to thruster distances because the longer wavelength beam spreading is orders of magnitude more than for laser wavelengths.

2. CURRENT STATUS OF LASER SYSTEM TECHNOLOGY

The missions that can be performed by laser propulsion depend a great deal on the laser power available and beam transmission quality. The current status of these issues are reviewed in this section.

2.1. AVAILABLE LASERS

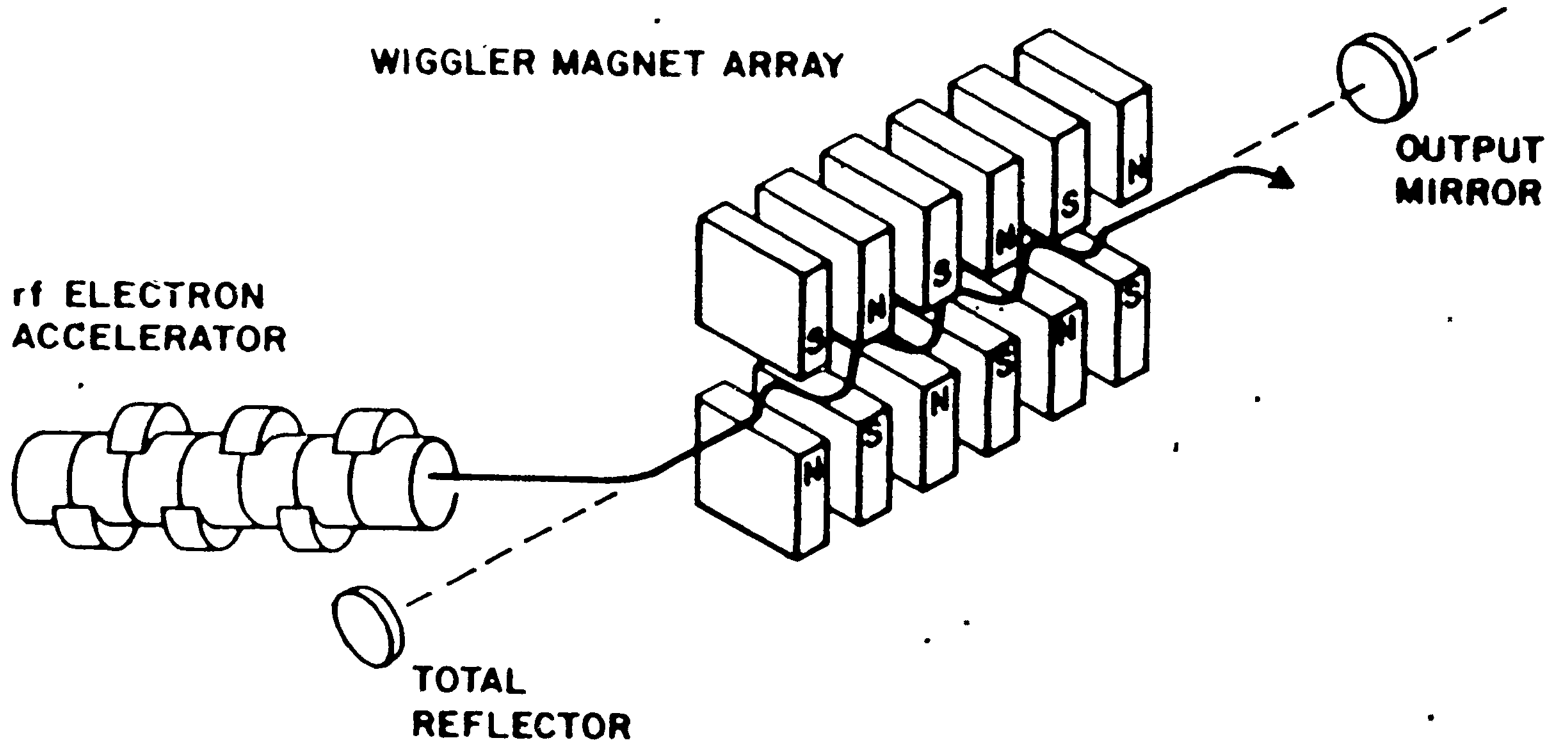
For useful payloads, the required laser power is 10 MW for orbit-to-orbit maneuvering and 1 GW for earth-to-orbit launching[14]. Current lasers can deliver power levels of less than a megawatt which is orders of magnitude below the requirement. Scaling to the higher powers required; however, seems to have no fundamental limitations. Lasers capable of producing these higher power levels have been under development for weapons applications for a number of years, and several different laser technologies have been proposed.

The earliest development efforts were directed toward continuous electric discharge and gasdynamic carbon dioxide lasers operating at a wavelength of 10.6 microns[26]. Electric discharge lasers evolved to electron beam pumped transverse flow systems that are currently used for industrial processes. Chemical lasers operating at wavelengths from 2.5 to 4 microns using hydrogen and deuterium fluoride have been reported to operate at powers in excess of 2 MW[26]. Some large high average power carbon dioxide pulsed laser systems have been developed with microsecond pulse duration and repetition rates of tens of Hertz to kilohertz. Recently, there have been some efforts to develop short wavelength (ultraviolet) excimer lasers into high average power

pulsed systems[26].

The advent of the Strategic Defense Initiative (SDI) has accelerated the development of high average power free electron lasers (FEL) and the concept of large phase-locked diode arrays[13]. In principal, the FEL (Figure 6 [27]) can operate over a wide range of wavelengths from tenths of a micron to more than ten microns and at efficiencies greater than 60% using electrostatic accelerators[28]. This is greater than the 20% and 10% efficiencies of carbon dioxide and chemical lasers respectively[29]. There are two basic types of FEL currently under development for high power applications: the induction linear accelerator (linac) and RF linac. The induction linac amplified laser pulse has a duration of tens of nanoseconds and have a repetition rate of a few kilohertz. The RF linac FEL has a pulse format consisting of a train of pulses of tens of picoseconds duration, and a repetition rate of tens to hundreds of megahertz. The short interpulse time of the RF Linac free electron laser gives a quasi-steady output that may be suitable for propulsion systems utilizing continuous laser sustained plasmas[26-28].

Lee[6] discusses the details of a solar-pumped laser (Figure 7). He concludes, based on the De Young's laser system study[7], that it is feasible to operate a solar-pumped 1 MW iodine laser system with a mass of 92,000 kg in a high (6378 km) orbit. The mass of



WIGGLER MAGNET ARRAY
rf ELECTRON
ACCELERATOR
OUTPUT
MIRROR
TOTAL
REFLECTOR

FIGURE 6

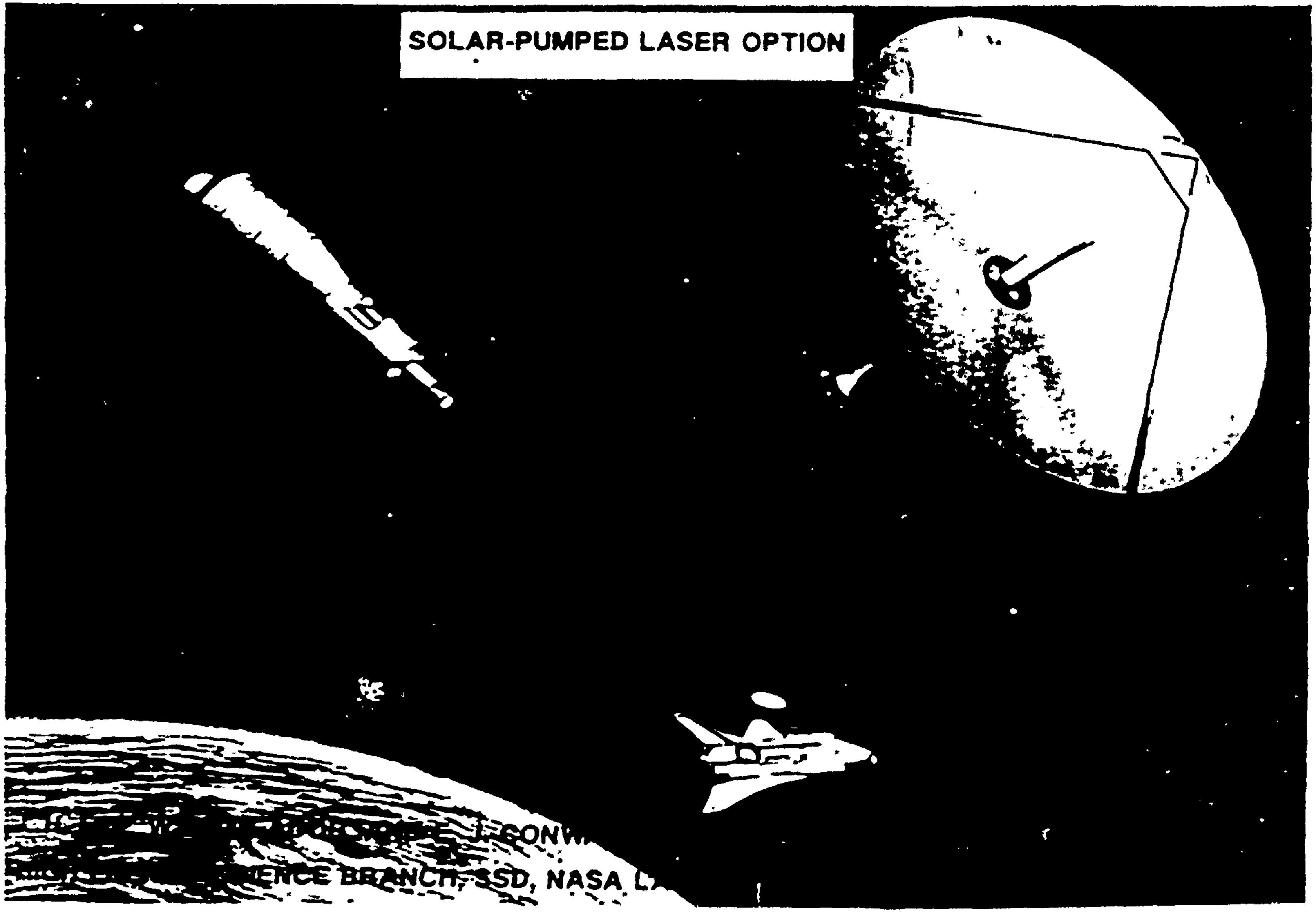


FIGURE 7

the system corresponds to the payload capacity of four space shuttle flights. Since there seems to be no fundamental limit for scaling this system, the requirements of laser propulsion could be met by future development of solar-pumped iodine lasers.

Future developments in diode array lasers may provide the required power at wavelengths near 1 microns[26]. It is too early to determine what laser wavelength and pulse format is most likely to become available for laser propulsion, and the ultimate choice is likely to be determined by laser developments for other applications requiring high average power.

2.2. BEAM TRANSMISSION

The most troublesome aspect of the Ground Based Laser/Space Based Relay system for propulsion is atmospheric transmission[26,30,31]. The major concerns for atmospheric propagation are :

a) Raman Scattering where non-linear problems arise below 3 microns.

b) Atmospheric absorption and scattering by particulates. However, if the laser wavelength is 2.2 micron, the atmosphere is transparent and there is no absorption.

c) Thermal blooming which is refraction caused by the heating of the air in the beam's path (nonlinear scattering).

d) Distortion and scattering of the beam by atmospheric turbulence (large or fine scale turbulence).

e) Optical losses such as mirror absorption,scattering etc. Atmospheric scattering can be counteracted by the use of adaptive optic techniques that dynamically sample the reflected beam and alter the figure of the mirror. Several approaches include piezo-electrically driven mirrors of both segmented and deformable membrane, and electro-optical devices (particularly non-linear phase conjugators). Requirements for vigorous turbulence correction will require a frequency response of 3 kilohertz[30]. In the near term, this requirement will probably dictate a segmented approach to construction of the phase adaptive mirror, rather than the deformable membrane approach[30].

Nonlinear scattering (Raman, thermal blooming etc) of the beam depends both on the wavelength and the peak intensity of the beam, and these factors become an issue in the delivery of a high average power beam through the earth's atmosphere. In general, the longer the wavelength of the laser, the larger the size of the mirror that is required to propagate the beam a given distance, and the larger the size of the mirror that is required to intercept the beam. Since large mirrors are heavy and difficult to fabricate, there is incentive to use shorter wavelengths. On the other hand, shorter wavelengths increase the beam intensity along the propagation path and increase the

problems with nonlinear scattering in the atmosphere. It has been suggested that a compromise that may be nearly optimum would use an infrared wavelength near 2.2 microns[14].

Mirrors required for a space based laser could be smaller and lighter than for an earth-based laser. This is because space-based lasers have a much larger field of view, remain within range of the target a longer time, and are less affected by the Earth's atmosphere. As a result, beam spreading could be reduced close to the theoretical limit, resulting in lighter, smaller mirrors.

The collecting mirror refocuses the beam into the thruster through a small window. The laser beam must be introduced at the upstream of the flow in order to ensure stable heating of the working fluid. The reason is that most gases tend to become opaque to laser radiation at higher temperatures, so if the laser were introduced through the nozzle, the gases in the nozzle would tend to be heated and become opaque. This would block the heating in the absorption chamber and cause instability in the flow. Therefore the laser must pass through some type of window in order to enter the sealed absorption chamber. The main problem with windows is that they must be able to transmit the enormous energy fluxes without absorbing a significant fraction. Due to the high laser flux levels (for example, $3.2X10^5$ W/cm^2 for a 20

cm window in a typical 100 MW laser system[5]), the window will be subject to very high heat loads. The preferred approach is to use high-transmittance crystalline materials such as SrF2, ZnSe, or KCL[16]. Depending on the laser's wavelength and the window material selected, transmittance through the window can be as high as 99.98%[25]. This value will result in 20000 W to be absorbed by the window. The window can hold up only for a few seconds at these high power levels. Concepts for overcoming limitations include cryogenic fluid cooling, mechanical rotation, or aerodynamic windows[32].

Problems with the concentrator mirror are not as critical. This is because the beam is much more diffuse and intensities are much lower than for windows. Also, coatings now exist for the infrared wavelengths with reflectivities of 99.9% which means that the intensity of radiation absorbed by the mirror should be less than the intensity of light incident on a surface in normal sunlight[5].

3. CONTINUOUS LASER PROPULSION: RESEARCH STATUS AND NEEDS

In 1983 AFOSR began a new initiative in continuous beam energy propulsion systems and supported basic research at The University of Tennessee Space Institute[1], The University of Illinois[11], and The Pennsylvania State University[3]. Major questions which existed

at that time included whether or not laser energy could be absorbed directly by hydrogen, concern about the stability of the plasma, and the degree of control which could be exercised over the plasma location. As a result of these studies, it was shown that laser energy can be absorbed directly in flowing gases including hydrogen and it was concluded that both the size and location of the laser sustained plasmas can be controlled[13,33]. Detailed experimental investigations[34-39], have established that a continuous plasma could be operated stably in a convective flow with efficient absorption of the laser energy. The studies also revealed the complex interactions of the plasma with pressure, flow and the optical configuration of the focused laser beam. Recently, multiple plasmas have been sustained within a single chamber[40]. Experiments[13] have investigated plasmas sustained with a Gaussian beam and the decay characteristics of pulsed plasmas. Theoretical models for the interaction of the laser beam and the flowing plasma have been developed using an approximate model[41], a full Navier-Stokes formulation[42], and detailed calculations of the optical fields within a Navier-Stokes formulation[43].

The following sections are aimed at identifying the major research issues, both theoretical and experimental, which can provide sufficient background for the planned system studies and development programs.

3.1 THEORETICAL MODELS

The phenomena involved in laser supported plasma thrusters for space involve strong interactions among an intense optical field, a plasma, and a flow field. The determination of both the radiation field and the working fluid flow requires a coupled solution process. Two different parallel approaches have been pursued based on different laser interaction models. In the first approach, highly developed aerodynamic algorithms have been adapted to calculate low speed flows with strong heat addition[44]. This approach is attractive because it applies to either viscous or inviscid flows and provides high accuracy and efficiency. In addition, time dependent procedures are applicable to either steady or unsteady flows, making this a proach a candidate for studying both the steady flow characteristics of propulsion environments as well as the linear and nonlinear stability characteristics. Laser absorption phenomena is a low Mach Number and low Reynolds number process, and time-dependent models become extremely inefficient because the eigenvalues of the system become increasingly stiff as Mach number is reduced. There are artificial techniques to overcome this difficulty such as multiplying time derivatives with a matrix such that eigenvalues remain well conditioned at Low Mach numbers[45]. The most vigorous way is to use perturbation expansions of the equations of motion

at low Mach number limit to obtain a low Mach number system[44,46]. To ensure convergence of a numerical solution, an iterative technique can be modified to give a convergent solution to the desired flowfield, starting with the inviscid and then proceeding to the viscous problem[47]. This can also be achieved using upwind differencing which can be implemented as an optionally high-order differencing of pressure and convective terms in the equation system[48]. This method allows monotonic capturing of a shock wave, if it occurs, true physical zonal dependence, and removes the cell Reynolds number restriction. Another convergence technique consists of changing the flowfield (by adding numerical viscosity) until convergence can be attained. The coupling between flow field and laser energy is modelled as either discretizing the incident radiation field into rays and using Beer law for each ray[47] or using differential form of the incident radiation equation which allows a coupled solution of the incident radiation and gas dynamic equations on the same grid[48].

The second laser interaction model consists of steady-state, axisymmetric, laminar flow Navier-Stokes equations for compressible, variable property flow to simulate laser-sustained plasmas[49]. The thermophysical and optical properties incorporated in the calculations were full temperature and pressure dependent based on the local thermodynamic equilibrium. Geometric optics

were used to describe the laser beam which was assumed to consist of a finite number of individual rays and Beer's law was used to calculate the local intensity for each individual ray. The developed code has the capability to calculate complicated flow regions such as recirculating, subsonic, and supersonic flows, within a realistic rocket geometry[50].

As a summary, state-of-the-art models are capable of solving two-dimensional, axisymmetric, unsteady, full compressible Navier-Stokes equations coupled with laser radiation under certain conditions. But, due to the assumptions and the neglected issues which may be important for high power systems, state-of-the art models cannot accurately simulate the systems operating at high laser power levels. Those issues can be summarized as :

- Diffraction of the laser beam due to the finite aperture of the lens and refraction due to the inhomogeneous refractive index within the plasma should be incorporated into the models.
- Volumetric, six-dimensional wide-band plasma re-radiation model should be used in the models rather than optically thick or optically thin extreme cases which are currently used.
- Plasma chemistry should be included in order to predict frozen flow losses as well as contamination and plume radiation from the exhaust gases.

- Models should be extended to be transient, and three-dimensional in order accurately predict repetitive-pulse energy coupling to the plasma and multiple plasmas respectively, as well as the dynamic stability.
- Turbulence should be considered in order accurately predict coupling between the plasma and the surrounding cold flow and the effects on the mixing and absorption process due to the density variations.

The intensity distribution in the focal region resulting from the focusing of a coherent monochromatic laser beam must be predicted accurately in order to calculate coupling between the laser beam and the plasma. State-of-the-art models use two different approaches: Fourier optical analysis[51,52] and Ray tracing techniques[53]. The former treats the laser beam as an electromagnetic wave, while the latter assumes the beam to be particle-like. Fourier analysis can incorporate spherical aberration if second-order terms in the series expansion for the lens thickness is included[52]. The integral relationship describing the output field resulting from the propagation of the transmitted field over a distance can be calculated in terms of the Helmholtz wave equation using Green's theorem and the theory of Green's functions. The Ray tracing technique calculates the local laser intensity distribution through Beer's law. The major deficiency in the both models is the refraction of the laser

beam, due to the inhomogeneous refractive index within the plasma[26]. Temperature gradients affect the refractive index, hence, beam reflection varies considerably from point to point. Since refraction phenomenon is coupled to the gas dynamics of the system, optical analysis and gas dynamics equations should be solved simultaneously using a variable index of refraction as a function of appropriate gas dynamic variables. Since refraction is also an important phenomena in atmospheric transmission (thermal blooming)[12] and laser weapon studies, a strong interaction among various research activities should be encouraged.

The major difficulty in the re-radiation problem is that it does not allow simple scaling parameters such as Reynolds numbers or Nusselt numbers to be used. The reason for this is that except for certain limiting conditions, radiation is a volumetric, as opposed to a point, phenomenon. The radiative flux at a point depends upon the emission from all other points inside the flow whereas, for example, the momentum flux is related only to the momentum fluxes in the immediate neighborhood of the point. The integro-differential nature of the radiation problem is a six-dimensional problem rather than a three-dimensional one. Besides this, the wavelength dependence represents an additional dimension. An exception to this is the optically thick limit where all photons at a point are created within a small

neighborhood of the point. Hence, the radiative problem becomes a local phenomenon in this limit and can be treated by the diffusion approximation. The optically thin limit can likewise be simplified because radiation is only emitted and not absorbed. Although the laser propulsion problem contains some wavelengths for which the plasma is optically thick and some for which it is optically thin, most wavelengths lie in the intermediate range between these two limits. Perhaps more importantly, the major effect of laser power scale-up on radiative losses is that fewer and fewer wavenumbers can be treated as "thin" and the transition from thin to thick (or intermediate) must be accurately modeled if scale-up predictions are to be realistic[33].

In addition to an accurate plasma re-radiation model, plasma chemistry should be incorporated into the analyses in order to predict frozen flow losses. Freezing has been assumed to occur at one of two locations in the nozzle: the throat where the Mach number is unity, or inside the supersonic portion of the nozzle where the flow velocity is Mach 2. The actual freezing location will depend on a diverse number of variables, primary among them being the length of the nozzle and the pressure level which directly affect the recombination rate. Longer nozzles provide more time for recombination while higher pressures increase the collision frequency. Frozen flow losses are considered to be small until somewhere above 1500 s specific impulse, at which

point rapidly increasing fractions of dissociated molecules leave the nozzle exit without recombination[3]. The second dramatic upsurge in frozen flow losses which take place above 2000 s specific impulse corresponds to freezing of the electron recombination processes[3]. In an actual case, the final concentrations of the species, such as ions, electrons, neutrals, atoms and molecules should be obtained from a complete system of equations including Arrhenius rate equations. If the restrictions stated above are true, dramatic increases in heat addition per unit mass could be made without observing any improvement in performance.

Although initial experiments reveal that a quasi-steady plasma can be maintained using repetitive pulse lasers, several research issues remain to be investigated both analytically and experimentally in order to predict the coupling dynamics between the laser beam and the plasma. This requires a full transient numerical model rather than models as used in the past. A typical RF Linac FEL peak power during 10-20 ps micropulses will be 2 to 3 times greater than the average power. Under these conditions it is likely that the plasma will not be in equilibrium during the absorption of the pulse, and could affect the fractional absorption of the laser beam or the radiation losses from the plasma[18]. This phenomenon precludes the use of the local thermal equilibrium assumption used in continuous wave laser propulsion

simulations, and the problem becomes computationally far more complex. The second issue is whether it is possible to initiate an undesired detonation wave rather than a deflagration wave, as a result of the enormous energy of the laser power peak. Previous detonation initiation studies[26] can be used for modeling the behavior of pulsed laser driven continuous laser propulsion systems.

One important concept for improving system efficiency is the use of enhanced thermal mixing between the hot plasma flow and the cooler surrounding flow. The goal of such mixing is to reduce temperatures as rapidly as possible downstream of the plasma where laser energy absorption is minimal but radiation losses are high. One approach to induce greater mixing is to increase turbulence in the downstream flowfield[54]. Another approach is the fragmentation of the incoming beam power and the creation of multiple plasmas[11,40]. In a realistic high power propulsion system, it may be necessary to operate with more than one plasma so that high specific impulses may be achieved while operating at high thermal efficiency with reduced residual thermal load on the lenses. In order to achieve an accurate simulation of the multiple plasma model, its three-dimensional nature and geometrical variations should be considered[29].

It has been both analytically and experimentally demonstrated

that plasmas are statically stable[55]. That is to say, if they are perturbed from their equilibrium location, they do not continue to drift further away, but instead return back to their original location. Dynamic stability of laser sustained plasmas has not been investigated in detail[33]. The issue here is that as a compression wave passes through an absorbing volume, it raises the density and temperature and, hence, the absorptivity as it passes. This increased absorptivity gives rise to an increase in the energy absorbed so the temperature is raised, thus reinforcing the pressure wave and leading to a possible disturbance growth. In an open environment or a large volume, such pressure perturbations die out and remain undetected but in a closed volume, such as the absorber of a laser rocket engine, they can amplify and lead to high pressure oscillations. One advantage here, as compared to the combustion instability problem is that the coupling is less complex[33]. The energy addition can probably be treated in quasi-steady fashion without a time lag, whereas in combustion problems it is the time lag which depends on the kinetics as well as droplet evaporation times, controls the instability.

3.2 EXPERIMENTAL MODELS

Experimental studies have shown that the plasmas are stable in a

convective flow, absorb a substantial fraction of the laser beam power up to 90%, and that a substantial portion of the absorbed power is converted directly to propellant enthalpy up to 38%[13,40]. Efficient ways were needed to couple laser energy into a working fluid without generating hardware-damaging plasmas or coupling instabilities. Several important new research tools were developed to permit the acquisition, reduction and analysis of the high resolution data obtained from these experiments. A new and improved method was developed, based on transform techniques, to perform a large number of Abel inversions required to reduce the experimental data[13]. The laboratory scale experiments revealed that a high efficiency , high specific impulse hydrogen thruster powered by beamed laser energy is feasible[35].

Ignition phenomena is also an important issue for an operational laser propulsion system. Currently, plasmas are ignited by focusing the laser beam onto metallic targets placed at the laser focus[38]. Three types of targets have successfully been used: zinc foils, tungsten rods, and injected aerosols such as water or deuterium. The last technique has proven to be unreliable, since the particles in the aerosol must be injected precisely at the laser focus point in order to produce ignition[29]. An alternative method of efficient ignition of plasmas by resonant UV laser multiphoton excitation has also been proposed[56].

Increasing the gas pressure causes a noticable rise in absorption at low laser powers, but this effect largely disappears at the higher power levels. Increasing the flow rate appears to produce a slight decrease in global absorption. The measured minimum maintenance power increases with focus spot size and flow rate, and decreases with gas pressure[40]. The percentage of the incident laser power which has been absorbed by the plasma, was measured by Krier[42] using the copper-cone calorimeter mounted at the top of the absorption chamber. The accuracy of the temperature, velocity, and concentration measurements can be improved relative to the current techniques through the use of laser-induced fluorescence techniques. Basically stated, laser-induced fluorescence is a diagnostic technique in which a low power laser is tuned to excite an electronic transition within an atom. When this excited state decays to ground, the emitted fluorescence can be used to determine several properties. The advantage to this approach is that measurements are instantaneous, and are unaffected by transmitted laser energy and plasma re-radiation[13,40].

Thus far, issues concerned with high power laser development, and pointing and tracking have not been discussed. Once the feasibility of continuous laser propulsion has been proven and high power laser development has been accelerated, several new technical challenges are envisioned. Two major issues which

should be investigated experimentally as well as theoretically, are scaling and the use of repetitive-pulsed lasers.

A major questions concerns scaling. The physics of high power continuous laser supported plasmas may be quite different from what we obtain from laboratory scale experiments. Even though laboratory experimental results can be predicted by the existing theoretical models, issues that are insignificant at low power may play a dominant role when the power is scaled-up. It is important to perform experiments with laboratory-scale lasers to quantify the effects of refraction, wide-band radiation, plasma chemistry, turbulence and mixing processes. We must also perform scaling experiments to identify unknown mechanisms which might become significant when the laser power is scaled up.

A second area that requires additional research is an assessment of the feasibility of using highly repetitive laser pulses in a quasi-continous wave fashion. Since practical laser propulsion systems require laser powers of 1 MW or greater, current technology suggests that a most likely candidates is the free electron laser. Such lasers do not operate in a continous mode but with a variety of pulse formats. The initial experiments conducted at the University of Tennessee Space Institute[13] have revealed that the recombination time of the plasma was of the order of one microsecond; much longer than the interpulse time of

46 nanoseconds characteristic of the RF Linac free electron laser. This result strongly suggests that a quasi-steady plasma can be sustained using a pulsed laser. The equilibrium of such plasmas and their absorption and re-radiation characteristics will be studied in a series of experiments planned at LANL[13].

4. CONCLUDING REMARKS

One of the objectives of this article has been to identify basic research issues for continuous laser propulsion systems and discuss possible strategies. It is clear that the continued development of laser propulsion requires a better understanding of losses including convective, radiative, frozen flow and mixing losses, in order to improve efficiency and consequently the feasibility of the laser propulsion systems. The task will require improved mathematical models to describe the physical phenomena occuring in laser propulsion systems in order to predict the scaling behavior.

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SECTION A

LASER PROPULSION

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Laser propulsion for missions in space is an advanced concept that promises specific impulse values two to four times higher than chemical rockets at thrust levels orders of magnitude higher than can be obtained with electric rockets. This promise of high thrust combined with high Isp is shared with nuclear rockets which have radioactivity and a large mass fraction due to reactor weight and shielding. Furthermore the technical problems known to exist with laser propulsion do not appear fundamental; and an economic justification for the concept has been concluded in separate studies by the AFAL, NASA, and DARPA. Despite these favorable indicators, laser propulsion lacks a complete demonstration nineteen years after its conception, its funding has fallen drastically over the past seven years, and the status of continuing effort has retreated from demonstration to research topic. The major current effort is being funded by the AFOSR.

In resolving the apparent contradiction between high promise and low interest, it is appropriate to note that

priorities for funding must take into account short term needs and difficulties as well as long range promise. At the AFAL significant funding ended in 1980 under a constrained budget, but with the tactic understanding that it would be reconsidered each year as the budget and technical conditions changed. The technical condition of most importance was the availability somewhere in the US of a large laser facility with which to do a meaningful thruster demonstration. The AFAL could not undertake such a facility. Coincident with that decision was a prioritization among several advanced concepts in which laser rockets were subordinated to solar rockets. There are some technical resemblances between a laser rocket and a solar rocket, but a salient difference also: sunlight is free, and lasers are costly. This observation has impact in immediate facilitization and also in the complexity of eventual operational systems.

The decision to emphasize solar over laser propulsion did not intent to overstate the similarities between the two concepts, although orbit raising, the niche most favored at AFAL for laser rockets, could be filled almost as well by a nearer term solar rocket. Orbit raising is also of obvious interest to SDI activities. Other SDI propulsion needs exist which would more clearly distinguish the differences between the concepts. These include boosters for low cost access to space and boosters for kinetic kill vehicles. Both applications require thrust levels that far exceed any believable solar rocket design, yet they might be accomplished with laser rockets, given a laser of

sufficient power. SDIO is currently conducting a laser propulsion program at Lawrence Livermore National Laboratory to meet their needs. Since powerful lasers are also being developed for weapons application, it may be that the missing link in the laser rocket chain is alreadly being forged.

Laser rockets are a generalization of beamed energy rockets which can include microwave powered rockets, and even particle beam rockets. Willinski of Hughes Aircraft conceived of ground based transmitters that projected microwave energy to power orbiting and even interplanetary propulsion systems before the operation of the first laser. He proposed a mode in which propellant would be heated directly for expansion through a nozzle, and a mode in which microwaves would be converted to electricity for operation of a plasma or ion engine, thus anticipating paths that laser propulsion advocates would follow later. He was aware of the large transmitting and receiving antennas required by the long wavelengths of microwaves. His ideas were later reproposed and elaborated upon by Schad and Moriarty of Raytheon.

A similar period of propulsion invention and reinvention followed the introduction of the laser, although a decade would pass before laser propulsion was cast into the high thrust modes described by Willinski for microwaves. Initially laser propulsion took the form of light sails in which laser photons were reflected off large diameter, low density structures

producing thrust by momentum exchange. The application in each publication was interstellar travel, a vast undertaking in which it was very easy to appreciate the virtues of an infinite Isp, even if thrust and propulsive efficiency were almost vanishingly small.

More earthly interest in laser propulsion awaited the high thrust mating of lasers to rocket working fluids. This idea apparently occurred first to R. L. Geisler at the AFAL although initial publication came some years later from several sources, apparently working indipendently. A U. S. patent was granted in 1974 to Minovitch.

AFAL experimental objectives were modest in terms of Isp sought. Limiting temperatures to 4000-4500 K would lower specific impulse by 200-300 sec, but make thermal control much easier. It would, however, necessitate a change in coupling mechanism. Initial AFRPL funding went to TRW to study the value o laser propulsion to the AF mission, compare it with other beamed energy concepts such as microwaves, compare it with other beamed energy concepts such as microwaves, and recommend critical technologies that would need to be developed, including identification of appropriate coupling techniques. Recommended coupling mechanisms included alkali metals to lower the ionization temperature, incorporation of particulate seedants, and incorporation of molecular seedants. A parallel in-house effort concluded that the molecular absorption technique was most

useful, and noted that water vapor was the most attractive seedant when considered in light of probable absorption coefficient and high temperature stability. Experimental work was contracted to United Technologies Research Center (UTRC) to determine the coupling efficience of CO_2 laser radiation into H_2 flows containing, H_2O and D_2O. Laser supported combustion waves using this non-plasma method were demonstrated for the first time at temperatures covering the range 2000-4000 K. Since the measured absorption coefficient was about ten-fold higher than band model calculations had indicated, a verification effort was funded. In a subsequent shock tube study at PSI it was determined that the absorption coefficient was more nearly in accord with band theory, and in fact low enough to reduce absorption efficiency unless the optical path were lengthened. It was proposed that thrusters could be kept within tolerable lengths by reflecting the beam across the chamber several times, but this suggestion was not tested before the AFAL laser propulsion effort was terminated.

AIR FORCE ASTRONAUTICS LABORATORY

LASER PROPULSION PLANS

LTC HOMER PRESSLEY
DR FRANKLIN MEAD

AFOSR LASER PROPULSION WORKSHOP
8–10 FEB 1988

BACKGROUND

WHY LASER PROPULSION?

* HIGH Isp POTENTIAL
* HIGH THRUST RELATIVE TO ELECTRIC CONCEPTS
* AVOIDS THE RADIATION AND MASS PENALTIES INHERENT WITH NUCLEAR PROPULSION
* TECHNICAL PROBLEMS ARE NOT FUNDAMENTAL
* ECONOMIC JUSTIFICATION CONCLUDED IN SEPARATE STUDIES BY AIR FORCE, NASA, AND DARPA

PROBLEMS

* LACKS COMPLETE DEMONSTRATION AFTER 19 YEARS FROM CONCEPTION
* REDUCED FUNDING FOR DEMONSTRATION
* LOW INTEREST

BRIEF HISTORY

BEAMED ENERGY ROCKETS

* MICROWAVES – WILLINSKI (1959)
* PARTICLES
* LASERS – LIGHT SAILS – FORWARD (1962)
  – LASER ROCKETS – GEISLER (1969)

AFRPL PROGRAM

* INITIATED CIRCA 1972
* LIMITED TEMPERATURES BELOW 4500
* TRW MISSION STUDY
  - LASERS VS OTHER BEAMED CONCEPTS
  - IDENTIFIED CRITICAL TECHNOLOGIES
  - COUPLING TECHNIQUES
* PARALLEL IN-HOUSE STUDY
  - COUPLING EFFICIENCY OF CARBON DIOXIDE RADIATION TO HYDROGEN SEEDED WITH WATER
  - ACHIEVED LASER SUPPORTED COMBUSTION WAVES OF 2000-4000 K
  - ANOMALOUSLY HIGH ABSORPTION COEFFICIENT
* PSI SHOCK TUBE TESTS
  - ABSORPTION COEFFICIENT IN ACCORD WITH BAND THEORY
  - ABSORPTION COEFFICIENT LOW ENOUGH TO REDUCE ABSORPTION EFFICIENCY UNLESS OPTICAL PATH LENGTHENED
  - SUGGESTED APPROACHES NOT TESTED BEFORE LASER PROPULSION EFFORT TERMINATED

RESOLVING APPARENT CONTRADICTION

HIGH PROMISE/LOW INTEREST

* FUNDING PRIORITIES CONSIDER SHORT TERM NEEDS AND DIFFICULTIES AS WELL AS LONG RANGE PROMISE
* REQUIREMENT FOR LARGE LASER FACILITY FOR THRUSTER DEMONSTRATION

MISSION POTENTIAL

* ORBIT RAISING
* LOW COST ACCESS TO SPACE
* KINETIC KILL BOOSTERS

LASER PROPULSION WORKSHOP

University of Illinois
February 8-10, 1988

ABSTRACT

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PART I

Laser Propulsion: A Historical Perspective

The first laser was demonstrated by Maiman at Hughes Laboratories in 1960, and when the ruby laser was Q-switched in 1961 laser output power was sufficient to cause a plasma breakdown in the focused beam. Observations of breakdown led to the first analytical studies of the phenomena by Zel'dovich and Raiser and later by Raiser who developed theoretical models for laser detonation waves and subsonic laser supported plasmas.

Powerful continuous carbon dioxide lasers were developed in 1964, and Generalov et al demonstrated the first continuous laser sustained plasmas in 1972. These developments opened the possibility for the use of beamed power for space propulsion, and Kantrowitz and Minovitch proposed the use of lasers to power rockets using either pulsed or continuous lasers to generate high temperature plasmas or laser supported detonation waves to generate thrust. NASA Lewis Laboratories began a project about 1971 to develop a laser powered rocket using a continuous laser sustained plasma within a chamber to heat a hydrogen propellant that was then expanded through a nozzle to produce thrust. DARPA sponsored a study conducted by AVCO Everett Laboratories which investigated a number of possible configurations including the continuous laser sustained plasma, pulsed detonation waves generated on an external surface and pulsed plasmas created within a nozzle structure. A different concept using resonant molecular absorption of beamed laser energy to heat a mixture of hydrogen and the absorber was investigated by the Air Force Rocket Propulsion Laboratory.

In 1978 the NASA project was moved to NASA Marshall Spaceflight Center for further development and demonstration. Some preliminary experiments were performed in hydrogen using the Army's 30 kW MTU Laser. Subsequently, the laser was moved to a test area at Marshall and a test facility was constructed. To date, the laser has not operated successfully for more than a few preliminary experiments. In 1983 AFOSR began a new initiative on beamed energy propulsion systems and supported basic research at The University of Tennessee Space Institute (UTSI), The University of Illinois (UI), The Pennsylvania State University (PSU) and PSI, Inc.. These studies were directed at both continuous laser thermal propulsion and pulsed plasma breakdown within a nozzle structure. Detailed experimental investigations at UTSI and UI established that the continuous plasma could be operated

successfully in a convective flow with efficient absorption of the laser energy, and revealed the complex interactions of the plasma with pressure, flow and the optical configuration of the focused laser beam. Recent experiments at UI have sustained multiple plasmas within a single chamber, and recent experiments at UTSI have investigated plasmas sustained with a Gaussian beam and the decay characteristics of pulsed plasmas.

Theoretical models for the interaction of the laser beam and the flowing plasma were developed at UI using an approximate model and at PSU using the full Navier-Stokes formulation. Later, a comprehensive theoretical model was developed at UTSI that included detailed calculations of the optical fields within a Navier-Stokes formulation. Predictions from this model compared well with detailed measurements of experimental plasmas over a wide range of conditions, and the calculations were extended to predict the properties of laser sustained hydrogen plasmas and to design a 30 kW laser powered hydrogen thruster.

In 1986 Lawrence Livermore National Laboratory (LLNL) began an investigation into the use of a double pulse laser detonation on the surface of an external solid fuel to provide an earth-to-orbit launch capability for moderate sized payloads. Several contractors are currently supporting this investigation with both theoretical and experimental studies, but these studies are in their infancy and results can be expected within the next year.

Most of the AFOSR supported effort has been expended on the continuous laser sustained plasma concept, and the studies have shown that the plasmas are stable in a convective flow, absorb a substantial fraction of the laser beam power, and that a substantial portion of the absorbed power is converted directly to propellant enthalpy. Detailed design calculations using the UTSI code indicate that wall heat transfer requirements are within state-of-the-art and that a substantial portion of the plasma radiation can be utilized in a regenerative cycle. These calculations indicate that a high efficiency, high specific impulse hydrogen thruster powered by beamed laser energy is feasible, and further research should evaluate the effects of scaling to higher powers and the pulse formats that are likely for high power free electron lasers.

PART II

Experimental Research at UTSI

The experimental investigation of laser sustained plasmas at UTSI began in 1983 with the primary objective to determine whether the plasma was stable in a forced convective flow. The experiments utilized a surplus 1.5 kW unstable oscillator laser obtained from US Army Ballistic Research Laboratories (BRL) to sustain plasmas in flowing argon. Advanced diagnostic techniques based on digital imaging of the plasma continuum radiation were developed to provide an efficient way to measure the plasma temperature field with high resolution. The initial results were encouraging and revealed the interdependence of the pressure, power and flow velocity in determining the position and size of the plasma within the focal region of the laser beam. However, in the initial experiments the flow velocity was of the same order as the velocity induced by thermal buoyancy and another set of experiments was performed to verify stability in flows dominated by forced convection.

Several important new research procedures were developed to permit the

acquisition, reduction and analysis of the high resolution data obtained from these experiments. A new and improved method was developed, based on transform techniques, to perform the large number of Abel inversions required to reduce the experimental data. This method reduced the computer time required to process a single image from 20 hours to 5 minutes, and improved the accuracy of the inversion. A geometric raytracing technique that included the refraction of the beam by the plasma was developed to determine the power absorbed from the laser beam using the measured temperature field of the plasma and the known characteristics of the laser beam. Careful analysis of this data revealed the critical role played by the optical configuration of the sustaining laser beam, and experiments were conducted with several focal length systems to elucidate this effect. A new Fourier optics technique that included the combined effects of both diffraction and aberrations from the lens was developed to calculate the optical fields near the focus.

During this time, the detailed measurements were compared with predictions from a computer code developed at UTSI (discussed in a separate presentation by S. M. Jeng), and the agreement was excellent. The experiments revealed that a considerable degree of control over the plasma absorption, radiation and energy conversion could be obtained through the proper combination of f/number, pressure, power and flow, and experiments were performed in which more than 85% of the incident laser power was absorbed by the plasma and more than 45% of the absorbed power was directly converted into propellant enthalpy. A new state-of-the-art carbon dioxide laser was obtained by UTSI that was capable of producing a true TEMoo Gaussian beam with powers to 2 kW. Plasmas were sustained using this laser with much larger f/numbers in the same chamber as the earlier experiments, and the results confirmed our understanding of the critical role played by the optical configuration used to sustain the plasma.

Practical laser propulsion systems will require laser powers of 1 MW or greater, and current technology suggests that the most likely candidates are the free electron lasers. These lasers do not operate in a continuous mode but with a variety of pulse formats. In order to determine whether these pulse formats will be able to sustain a quasi-steady plasma, we have initiated experiments at UTSI to determine the characteristic relaxation time for a plasma created by a short laser pulse. Argon plasmas at pressures of 1 and 2 atm were created by focusing a nominal 100 mJ pulse of 15 ns duration from a XeCl excimer laser operating at a wavelength of 308 nm. The spectral emission from the decaying plasma was recorded by an optical multichannel analyzer (OMA) using a gate time of 10 ns. The spectrum indicated that the recombination time was of the order of a microsecond; much longer than the interpulse time of 46 ns characteristic of the RF Linac free electron laser operating at Los Alamos National Laboratory (LANL). This result strongly suggests that a quasi-steady plasma can be sustained using the RF Linac FEL pulse format.

Although it appears that a quasi-steady plasma can be maintained using the RF Linac FEL, several research issues remain. The duty cycle of the RF Linac FEL is of the order 2-4 x 10^{-4} and the peak power of the 10-20 ps micropulses will be much greater than the average power. Under these conditions it is likely that the plasma will not be in equilibrium during the absorption of the pulse, and it is unclear how this will affect the fractional absorption of the laser beam or the radiation losses from the plasma. Experiments are being planned to answer these important questions using the FEL at Los Alamos (LANL). Streak and framing images of the plasma created

during a 100 microsecond burst from the laser will determine its time evolution and whether a quasi-steady plasma is produced. Direct measurement of the transmitted laser beam power will determine the fractional power absorption from the beam, and time resolved spectra will be obtained using the OMA to determine whether the plasma is in equilibrium during micropulse absorption.

The experimental research has shown that the cw laser sustained plasma is stable in a forced convective flow, and that the fractional power absorption and conversion efficiency can be controlled with proper combinations of pressure, flow and optical geometry. Theoretical calculations indicate that scaling to higher powers is consistent with the use of shorter wavelength lasers, but the effect of increasing optical depth on the radiative transport is unknown. The characteristics of a plasma sustained with FEL pulse formats is currently unknown, but experiments are being planned to resolve this issue.

Laser Propulsion: A Historical Perspective

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GL-0924

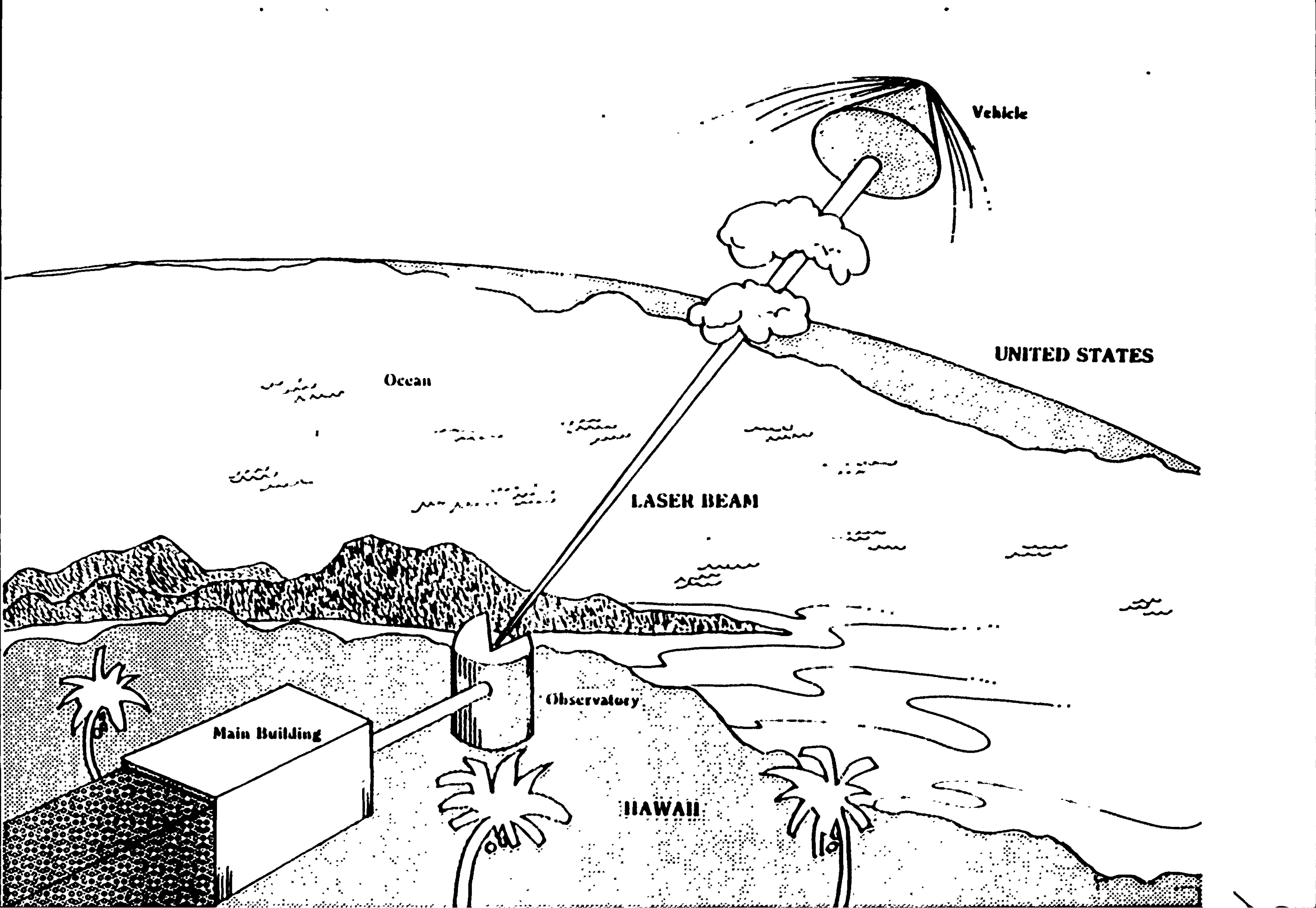
Laser Propulsion: A Historical Perspective

CLA Center for Laser Applications

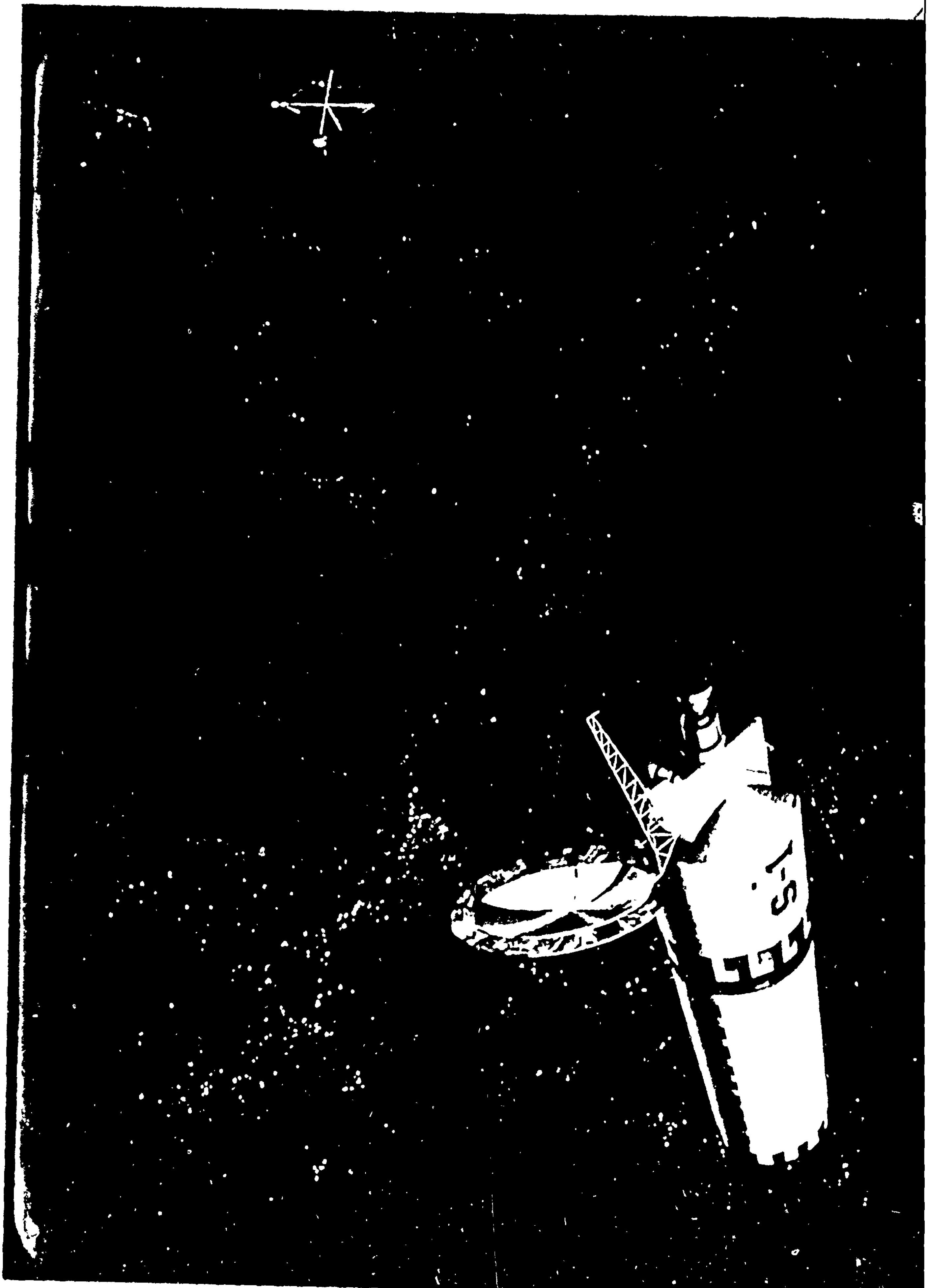
Discovery and Imagination

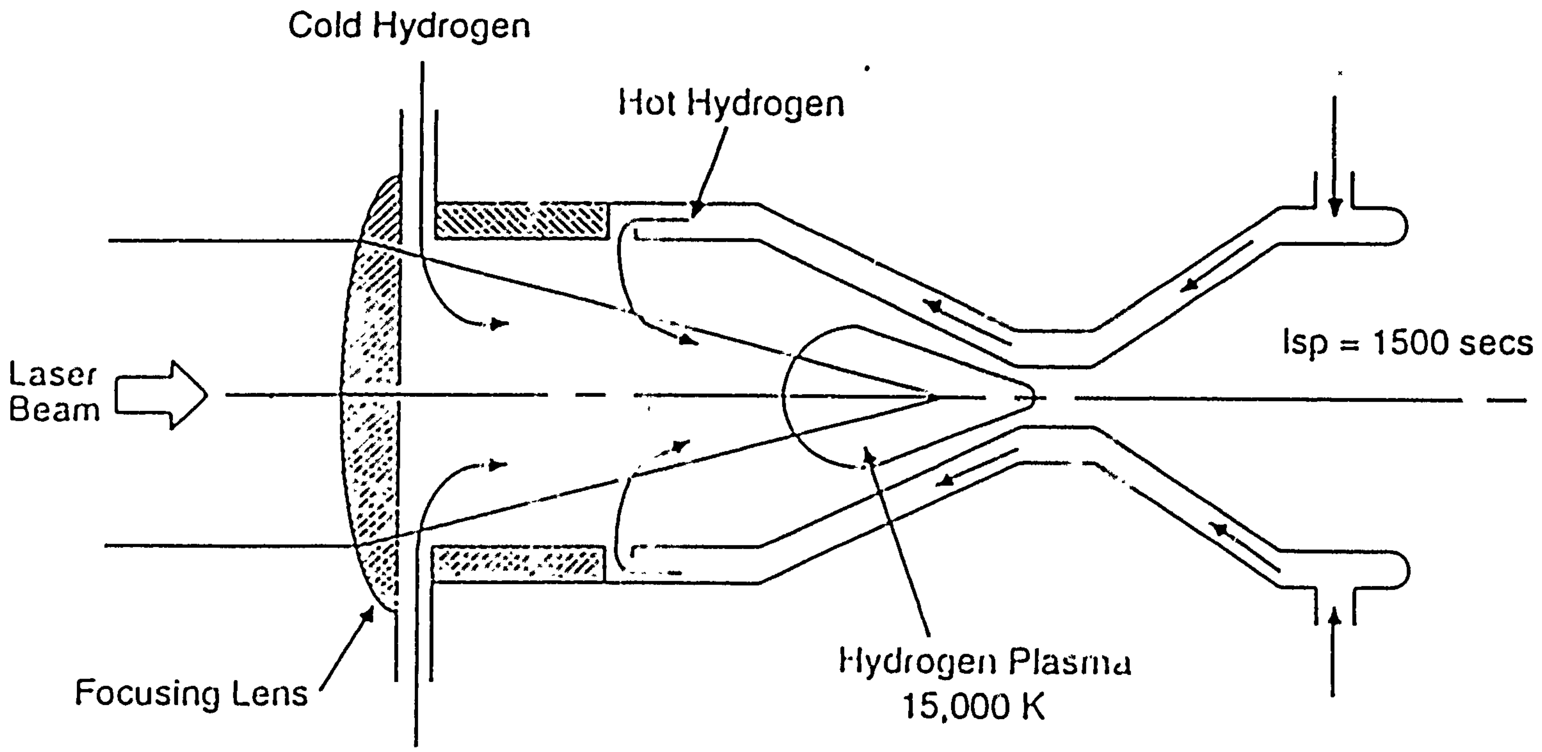
1954	The Ammonia Maser: Townes
1960	The Ruby Laser: Maiman
1961	Q-Switched Ruby: McClung and Hellwarth
1963	Optical Breakdown: Maker, Terhune & Savage
1964	CW Carbon Dioxide Laser: Patel
1971	Laser Rocket Concept: Minovitch, Kantrowitz
1972	CW Laser Sustained Plasma: Generalov et al
1983	AFOSR Initiative: Caveny

GL-0925



Vehicle
UNITED STATES
Ocean
LASER BEAM
Observatory
Main Building
HAWAII


S-I


Cold Hydrogen
Hot Hydrogen
Laser Beam
Isp = 1500 secs
Focusing Lens
Hydrogen Plasma
15,000 K

IL-0361

Laser Breakdown & Laser Sustained Plasmas

1963	Optical Breakdown: Maker, Terhune & Savage
1971	LSC Waves Observed: Conrad
1972	CW Laser Sustained Plasma: Generalov et al
1972	CW Laser Sustained Plasma: Franzen
1973	LSC Waves: Hall, Maher & Wei
1974	GDL Power to 400 kW: Klosterman & Byron
1975	Temperature Profiles: Fowler & Smith; Keefer, Henriksen & Braerman
1975	Low Power (25 W): Moody
1979	Molecular Gases: Kozlov, Kuznetsov & Masyukov; Conrad
1981	210 ATM Pressure: Carloff et al
1984	Flow Velocity: Carloff et al
1986	Laser Sustained Plasma Molecular Beam: Cross
1986	Detailed Measurements: Keefer, Welle & Peters
1987	Forced Convective Flow: Welle, Keefer & Peters
1987	Multiple Plasmas: Krier & Glumb
1988	Plasma Relaxation: Keefer & Sedghinasab

GL-0926

Laser Propulsion:
A Historical Perspective

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Theoretical Modeling

1965	Breakdown Model: Zel'Dovich & Raizer
1965	Supersonic Propagation "LSD" Model: Raizer
1970	One-Dimensional "LSC" Model: Raizer
1974	One-Dimensional Numerical Model: Jackson & Nielson
1974	Two-D Extension of Raizer: Balleh & Keefer
1978	One-D Time Dependent Model: Kozlov & Selezneva
1979	One-D Hydrogen Rocket Model: Kemp & Root
1982	Two-D Convergent Beam: Muller & Uhlenbusch
1984	Two-D Navier-Stokes: Carloff et al
1984	Two-D Navier-Stokes: Merkle
1985	Two-D Balleh-Keefer with Converging Beam: Glumb & Krier
1986	Two-D Coupled Navier-Stokes: Jeng & Keefer
1987	Rocket Thruster Model: Jeng & Keefer

GL-0927

Propulsion Activities

NASA	1972? NASA Lewis In-house & Contracted Efforts - PSI, Lockheed, Rocketdyne
DARPA	1977 AVCO Everett Study
NASA	1977 - NASA Marshall In-house & Contracted Efforts - PSI, US Army Micom, Lockheed, BDM, UTSI, UAH
	System Studies - Lockheed, Boeing, JPL
AFOSR	Contracted Efforts - Penn State, PSI, UTSI, University of Illinois
SDIO	LLL In-house & Contracted Efforts - AVCO, Spectra Technologies, NRL, PSI, RPI

GL-0928

AFOSR Activities

PRINCIPLE RESEARCH ISSUES

- Stability in Convective Flow
- Absorption Efficiency
- Conversion Efficiency
- Predictive Capability

CURRENT STATUS

- Plasmas are Stable in Convective Flow
- Absorption Efficiency > 80% Observed, > 99% Predicted
- Conversion Efficiency > 65% Observed & Predicted
- Excellent Predicted Capability for Plasma & Rocket

GL-0923

Whither Laser Propulsion ?

PRINCIPLE RESEARCH ISSUES

- Scaling - Power, Wavelength, Radiative Transfer
- Pulsed (FEL) Lasers - Quasi-Steady Plasmas ?
- Multiple Plasma Geometry
- Hydrogen Plasmas
- Thrust Prediction - Theory vs Experiment ?
- System Issues - Windows, Optics, Propellants, Weight
- Mission Studies - When does it make sense ?

THE COMPETITION

- Pulsed Laser LSD Wave
- Microwave - Beam or On-board
- Solar - Solid or Plasma Absorber
- Electric - MPD, Arcjets, Pulsed Plasma, RF Arcs, Railgun
- Magnetically Confined (Magnetic Bottle) Plasmas
- Nuclear - Fluidized Bed or Gaseous Core

GL-0930

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Experimental Research at UT Space Institute

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GL-0931

Experimental Research at UT Space Institute

CLA Center for Laser Applications

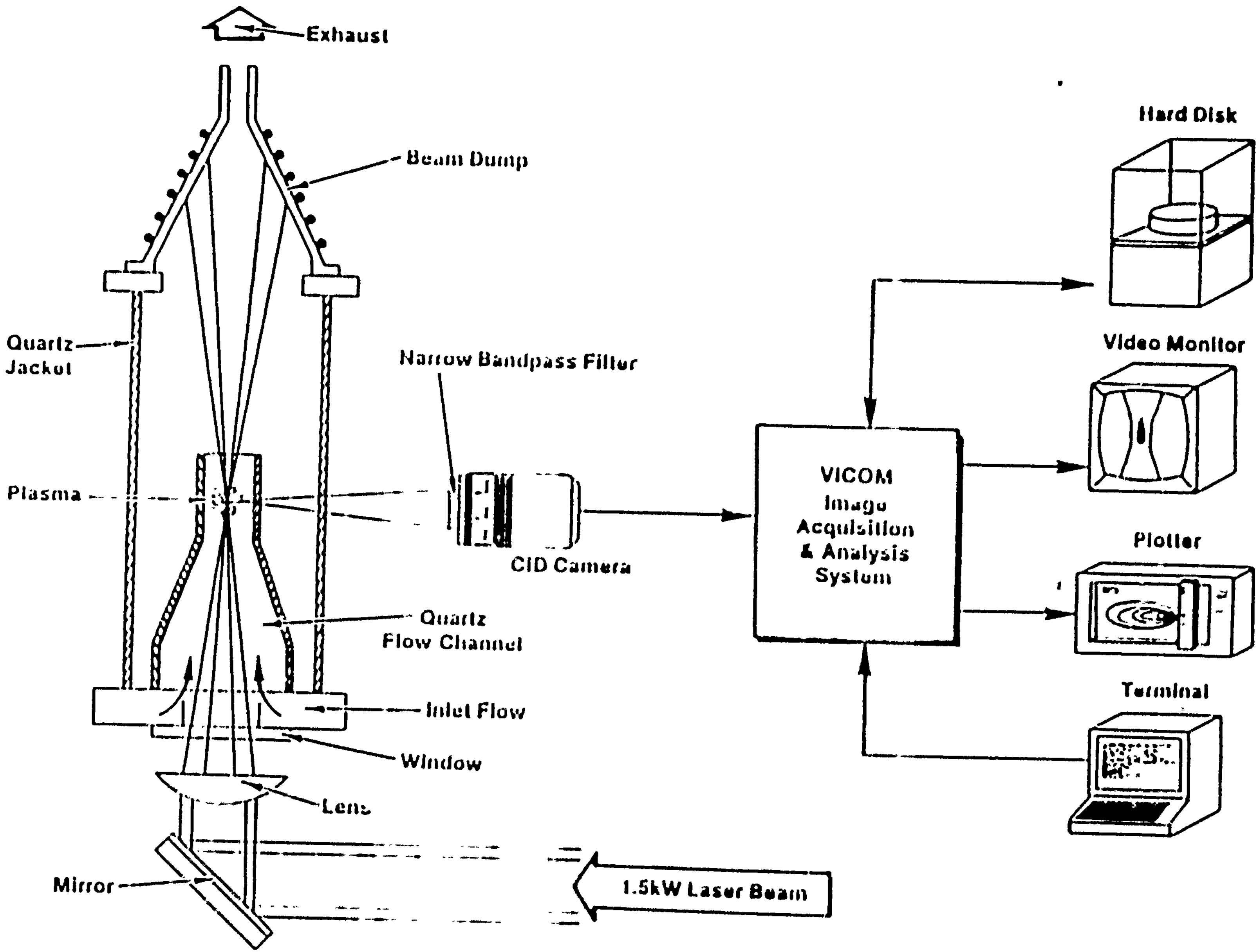
OBJECTIVES

- Stability in Convective Flow
- Absorption Efficiency
- Conversion Efficiency
- Pulsed Behavior

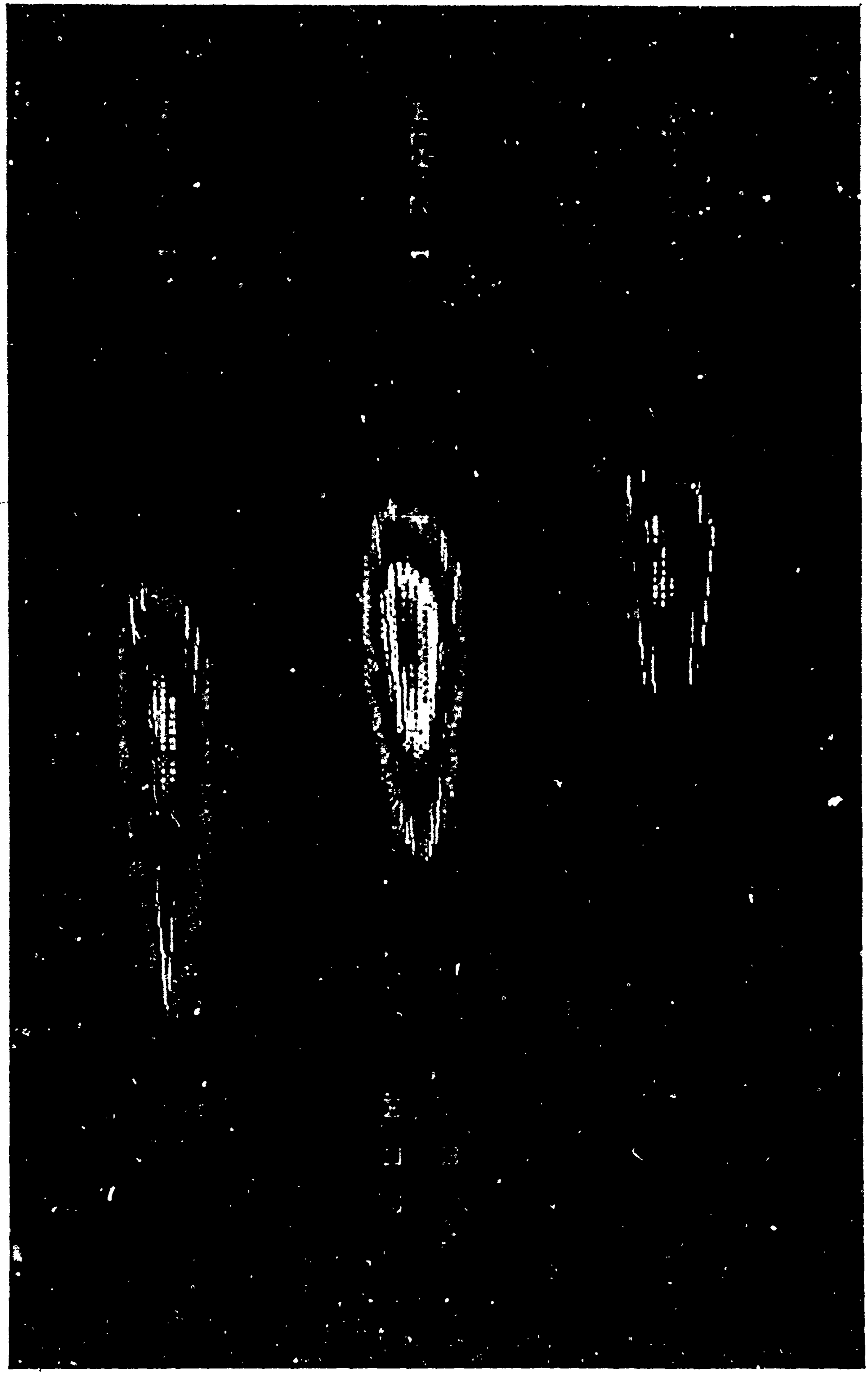
APPROACH

- Small, Good Beam-Quality Laser & Argon Plasmas
- Develop Efficient Optical Diagnostic Techniques
- Determine the Detailed Internal Energy Balance
- Compare Detailed Measurements with Theoretical Models
- Evaluate the Influence of Optical Geometry

GL-0932

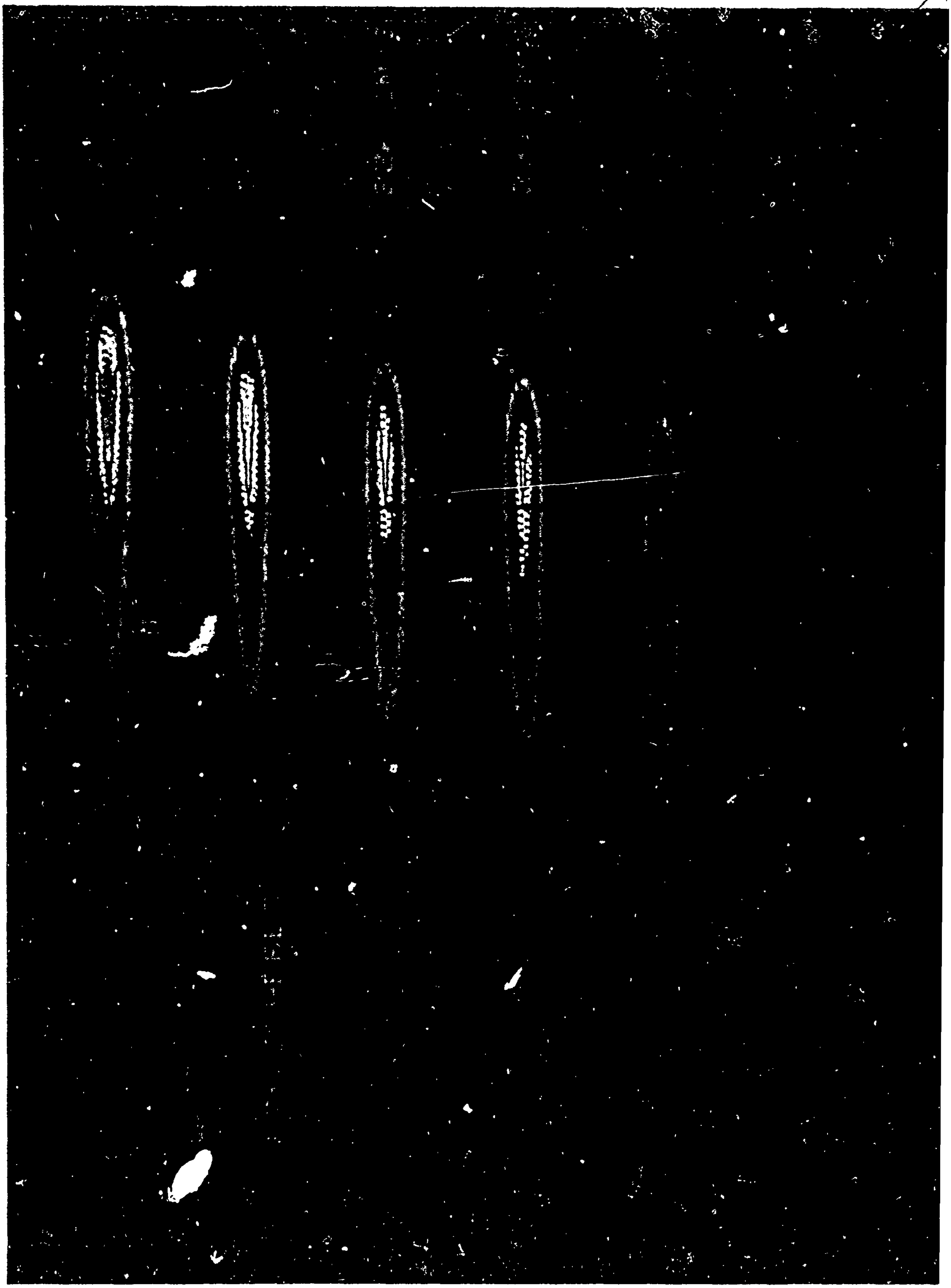


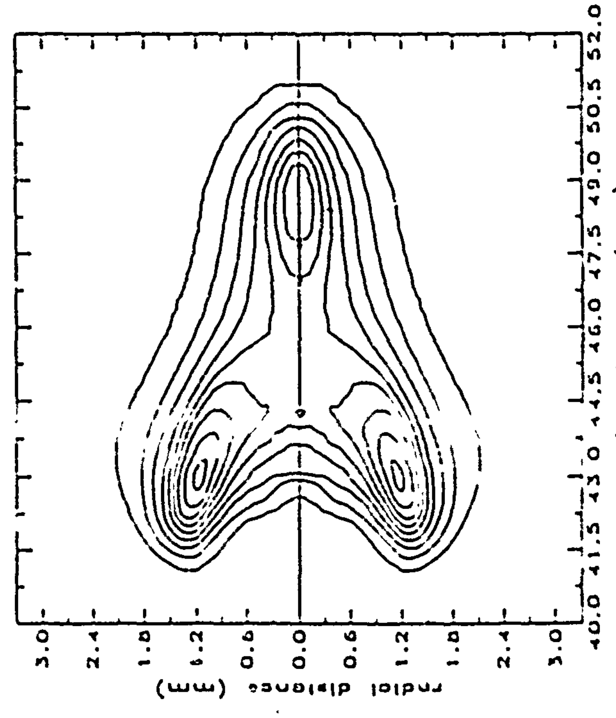
Schematic of the experimental apparatus.

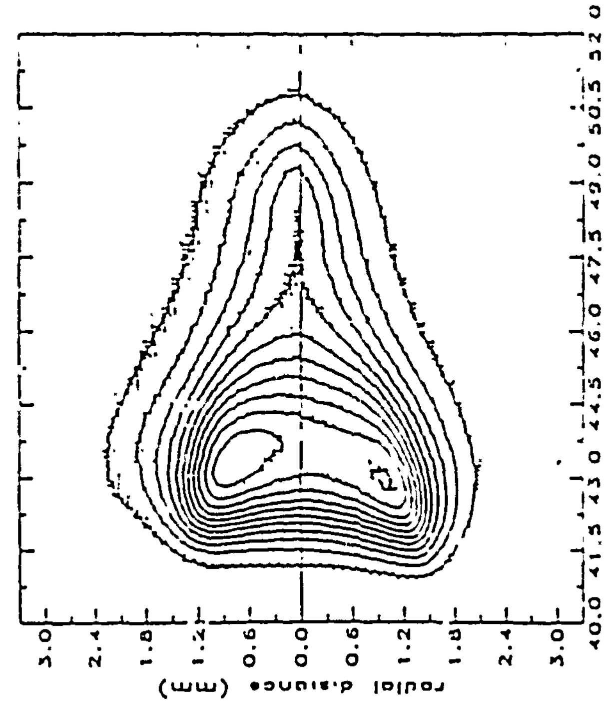


DIAGNOSTIC TECHNIQUE

- Acquire Digital Images of Narrow Wavelength Continuum Emission
- Use Transform Methods for Abel Inversion
- Determine Plasma Temperature Field Using LTE
- Calculate Power Absorption and Radiation Losses




radial distance (mm)
3.0
2.4
1.8
1.2
0.6
0.0
0.6
1.2
1.8
2.4
3.0
axial distance (mm)
40.0
41.5
43.0
44.5
46.0
47.5
49.0
50.5
52.0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axial distance (mm)
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46.0
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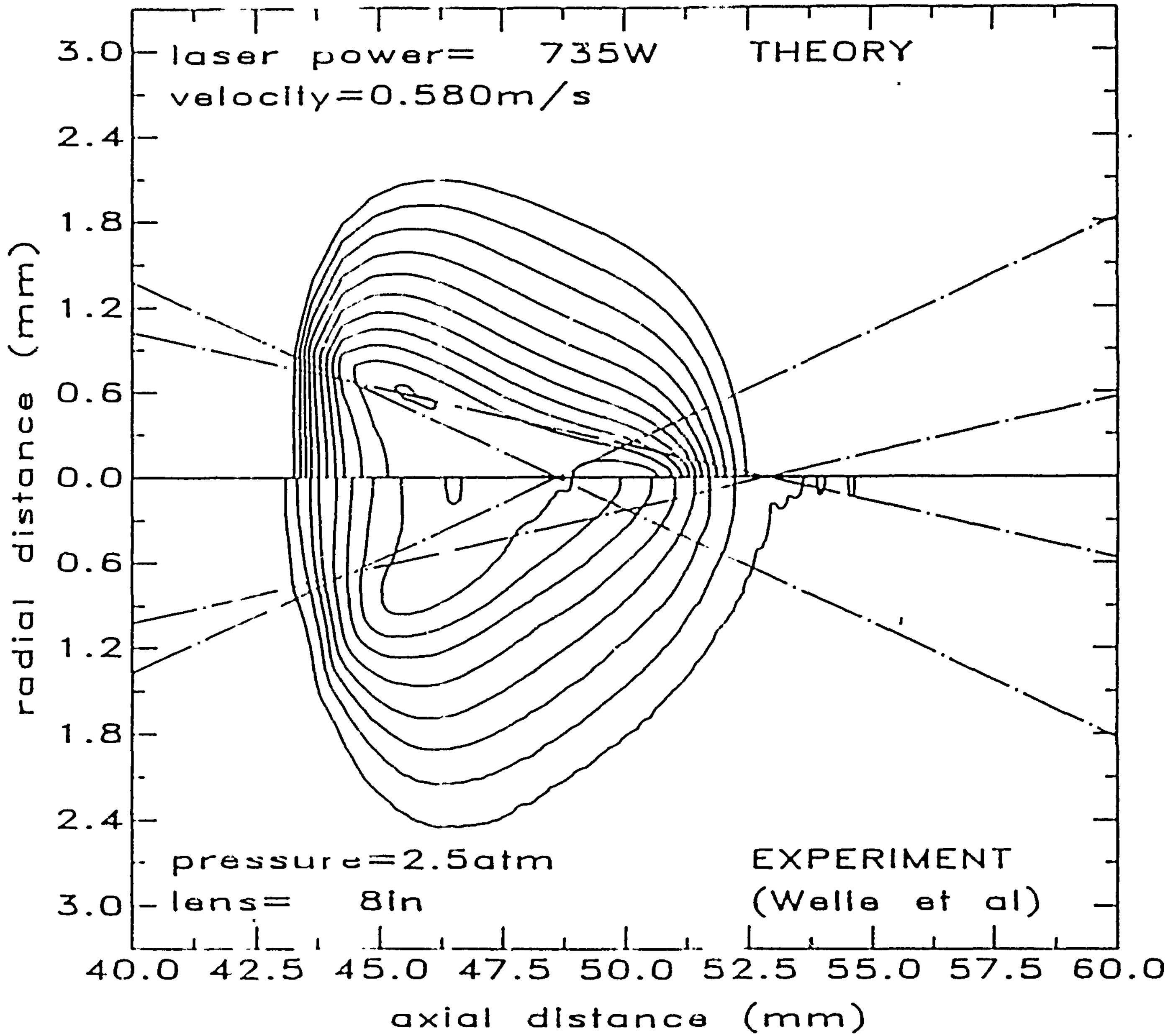
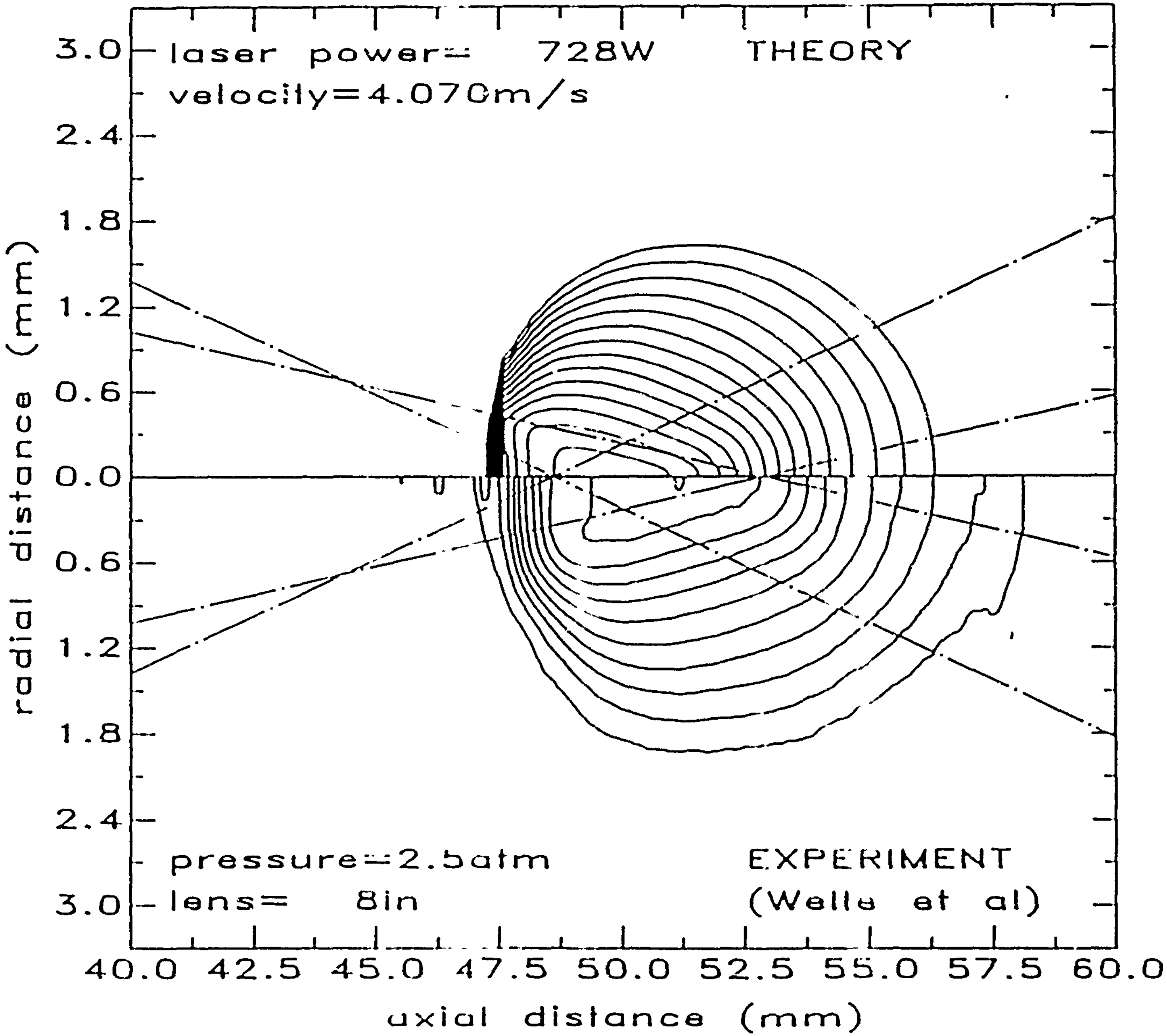
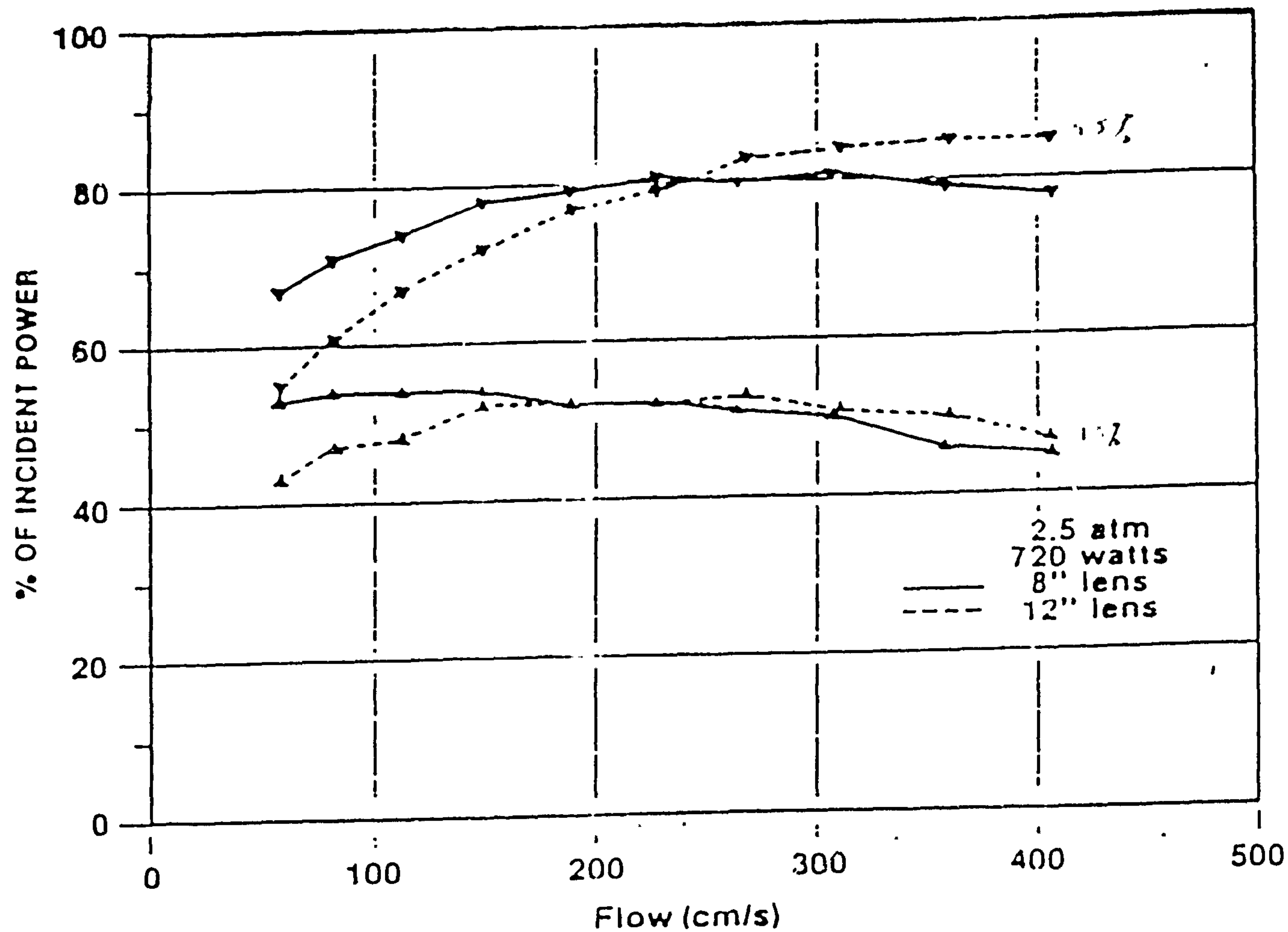
52.0



laser power= 735W
THEORY
velocity=0.580m/s
pressure=2.5atm
lens= 8in
EXPERIMENT
(Welle et al)
radial distance (mm)
axial distance (mm)
3.0
2.4
1.8
1.2
0.6
0.0
0.6
1.2
1.8
2.4
3.0
40.0
42.5
45.0
47.5
50.0
52.5
55.0
57.5
60.0



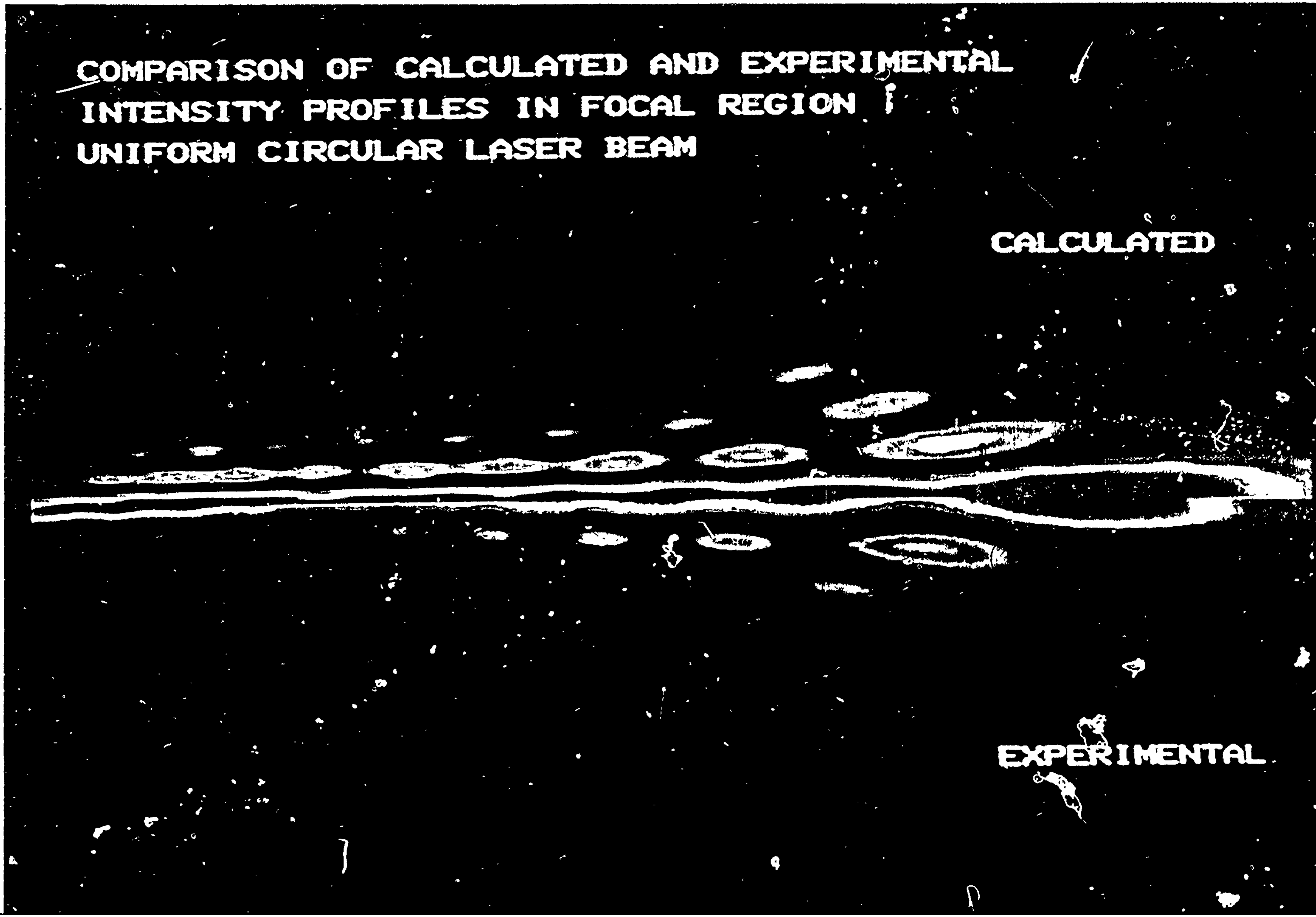
laser power= 728W
THEORY
velocity=4.070m/s
pressure=2.5atm
lens= 8in
EXPERIMENT
(Wells et al)
radial distance (mm)
axial distance (mm)
3.0
2.4
1.8
1.2
0.6
0.0
0.6
1.2
1.8
2.4
3.0
40.0
42.5
45.0
47.5
50.0
52.5
55.0
57.5
60.0

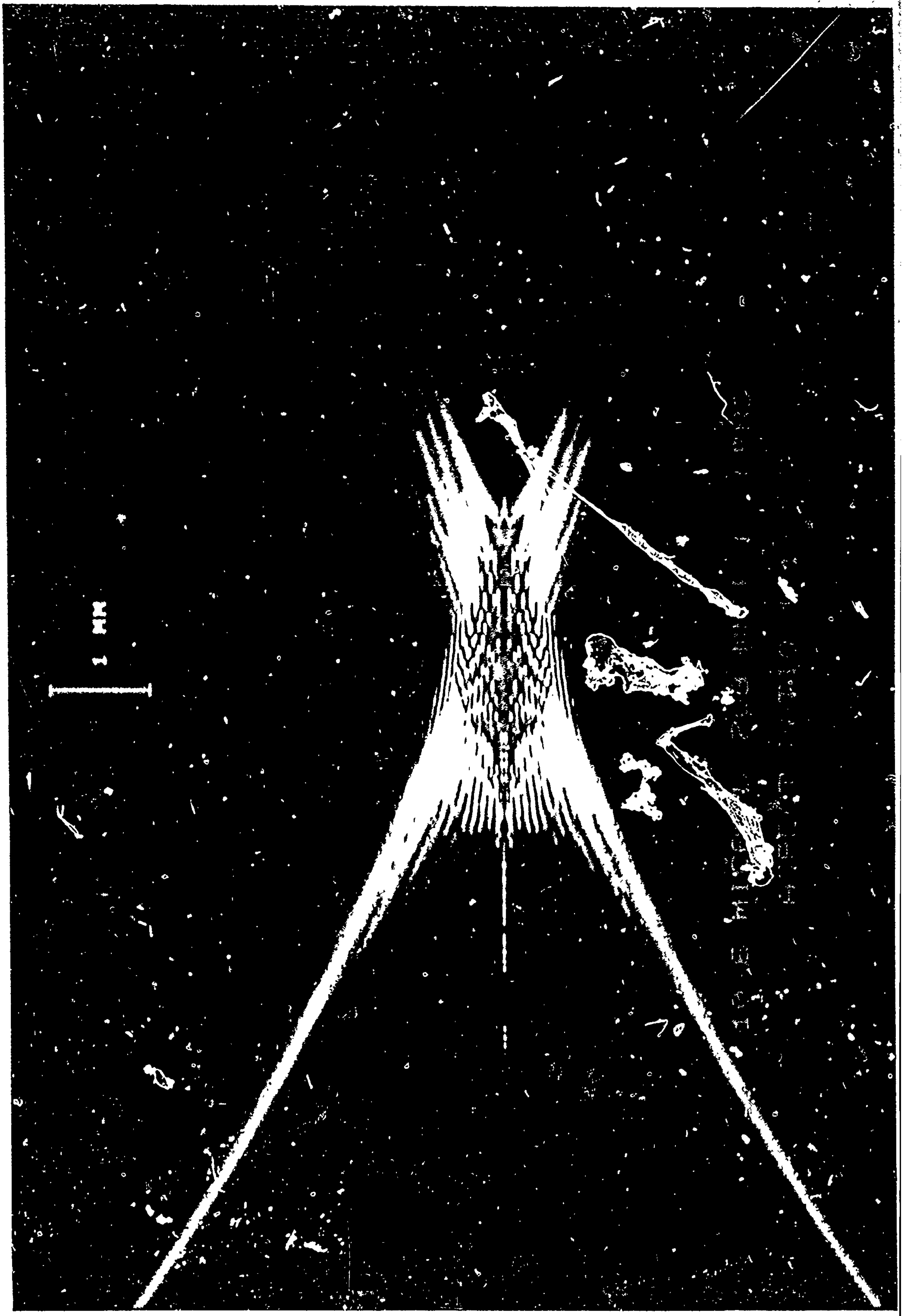


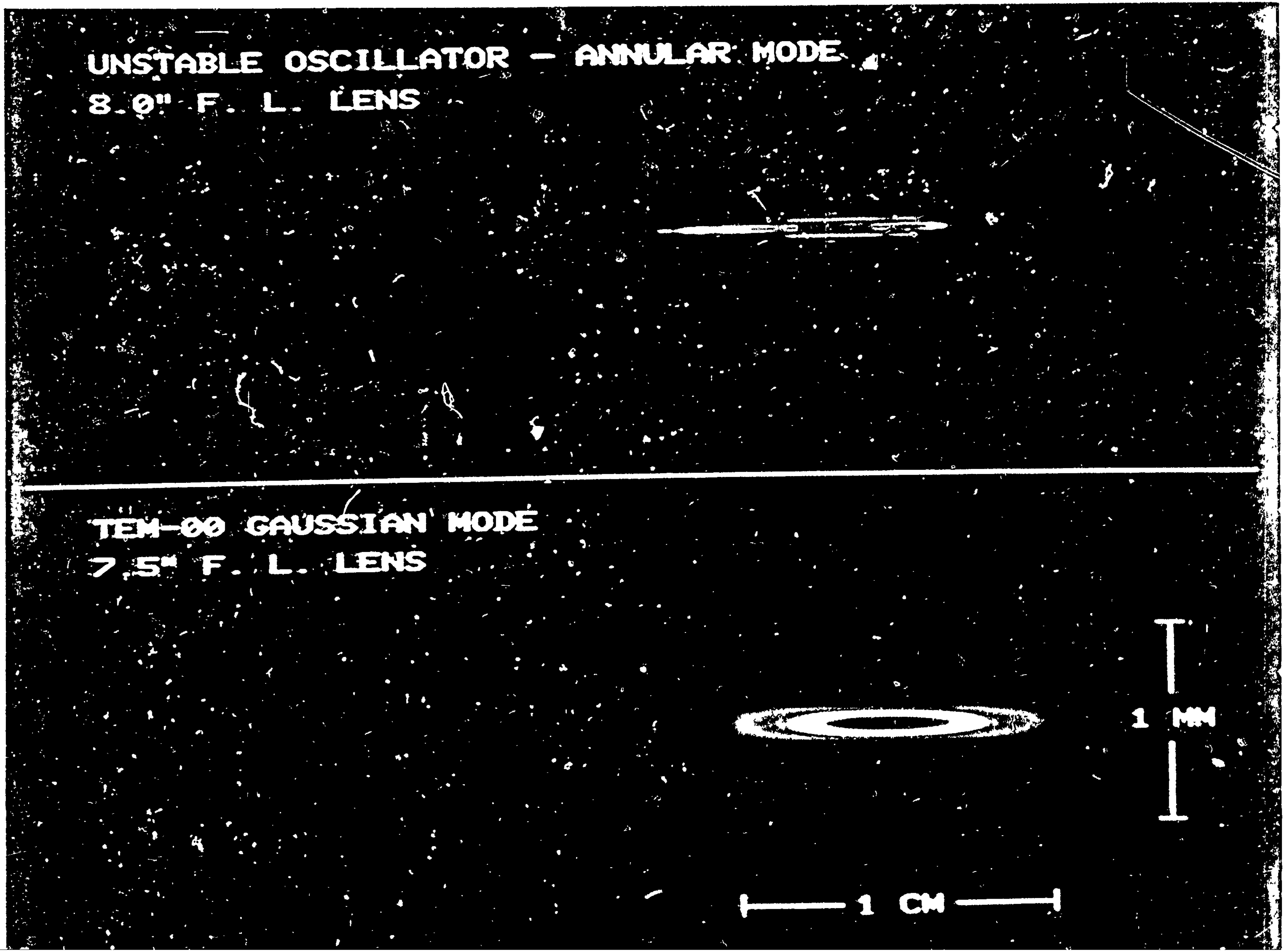
CLA Center for Laser Applications

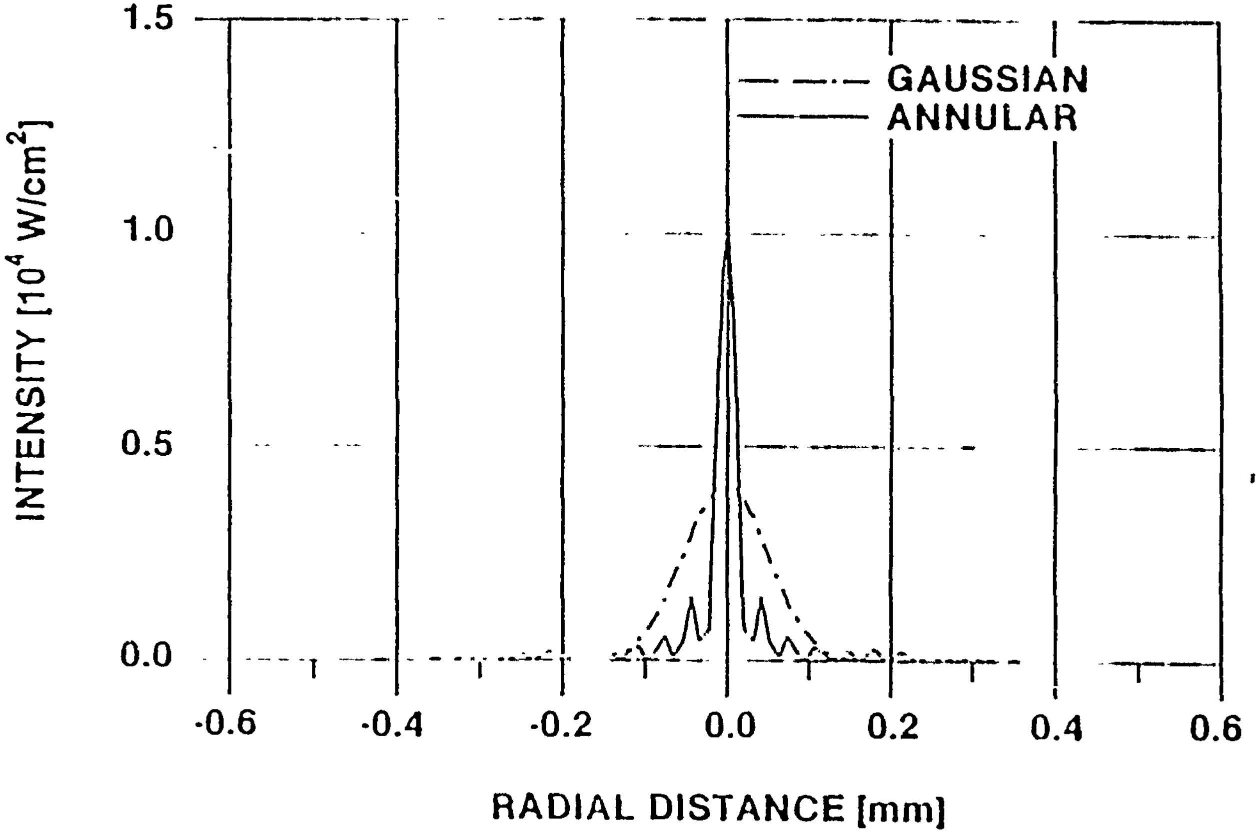
OPTICAL CALCULATIONS

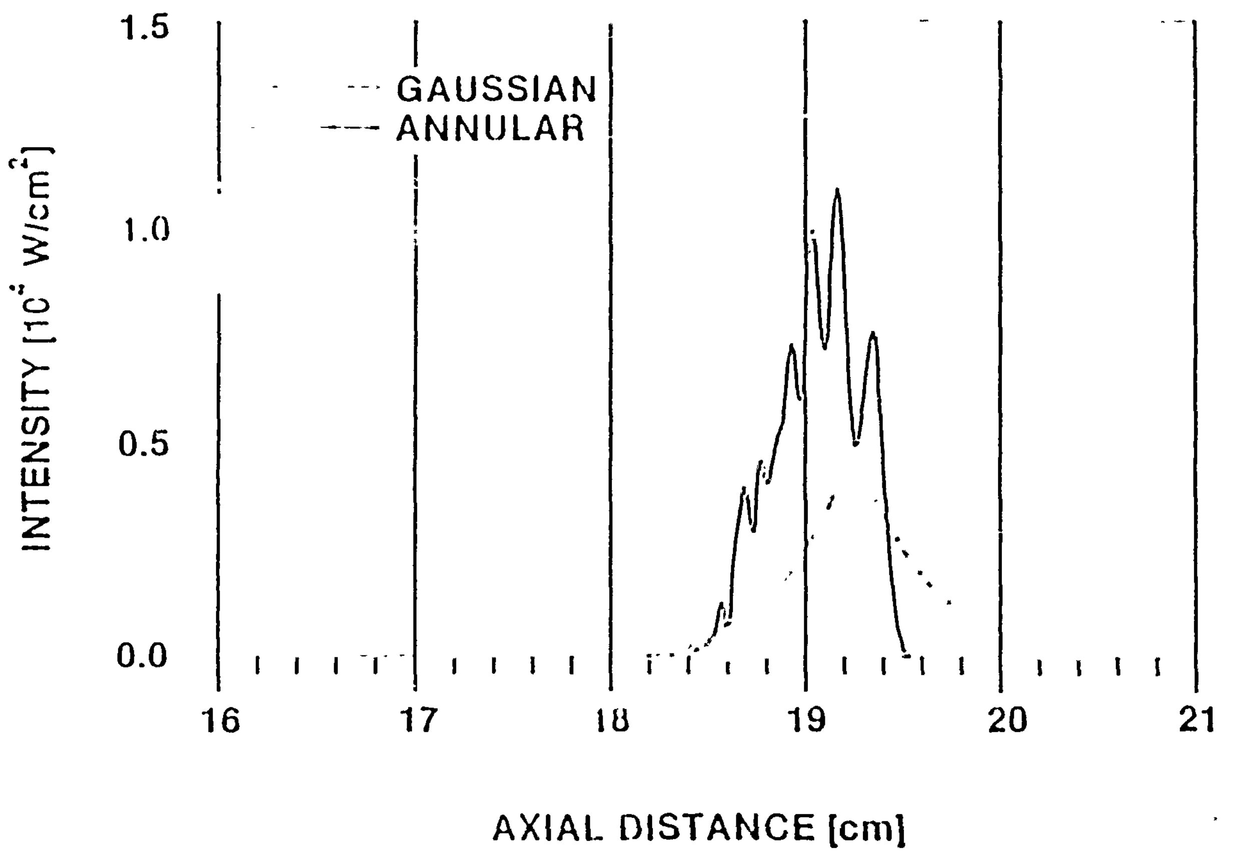
- Uses Fourier Transform Optical Methods
- Includes Effects of Both Aberrations and Diffraction
- Can Treat Arbitrary Input Distributions
- Has Been Verified Experimentally
- Does not Include Plasma Absorption or Refraction


COMPARISON OF CALCULATED AND EXPERIMENTAL
INTENSITY PROFILES IN FOCAL REGION
UNIFORM CIRCULAR LASER BEAM
CALCULATED
EXPERIMENTAL

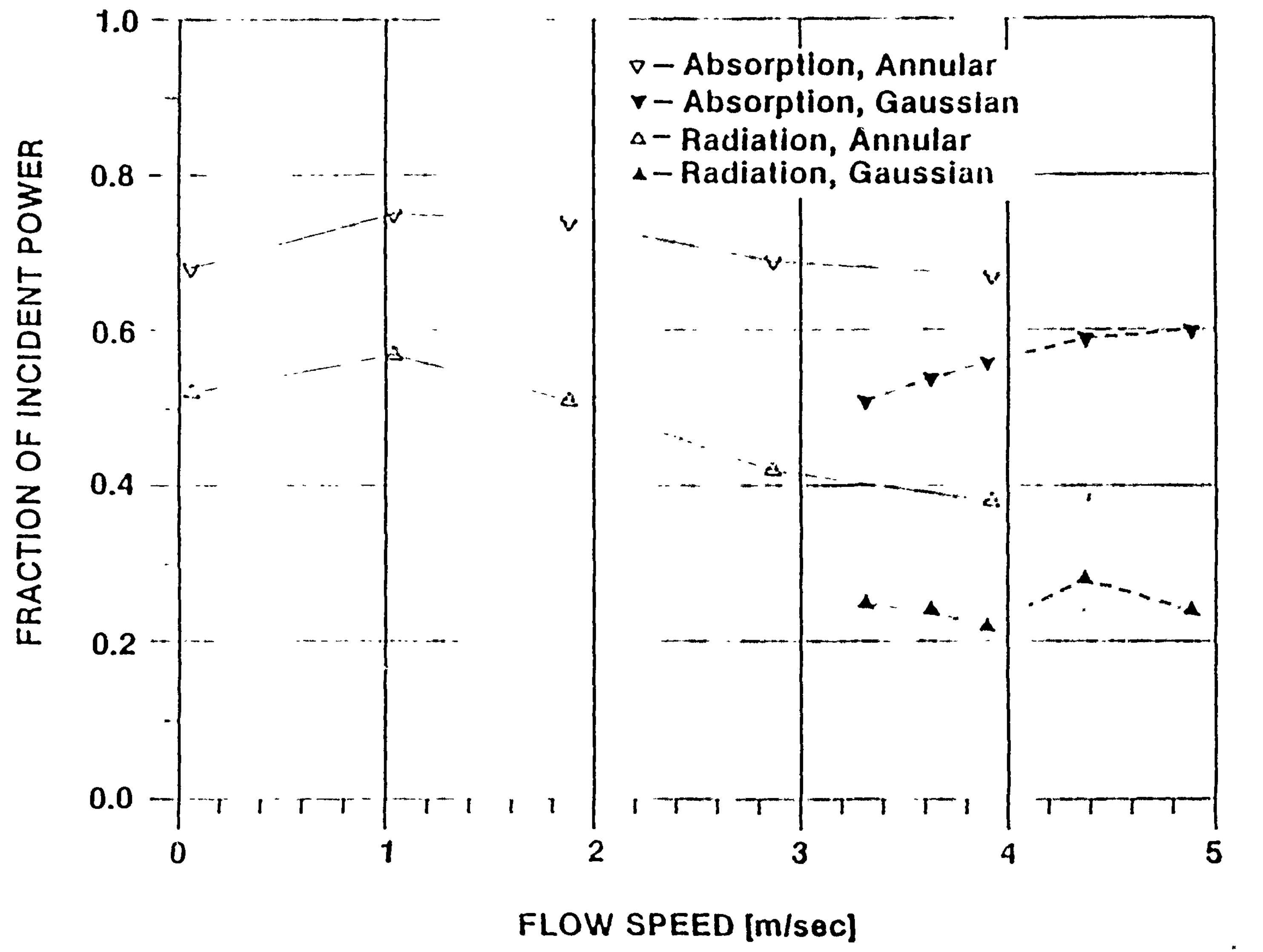



UNSTABLE OSCILLATOR - ANNULAR MODE
8.0" F. L. LENS
TEM-00 GAUSSIAN MODE
7.5" F. L. LENS
1 MM
1 CM

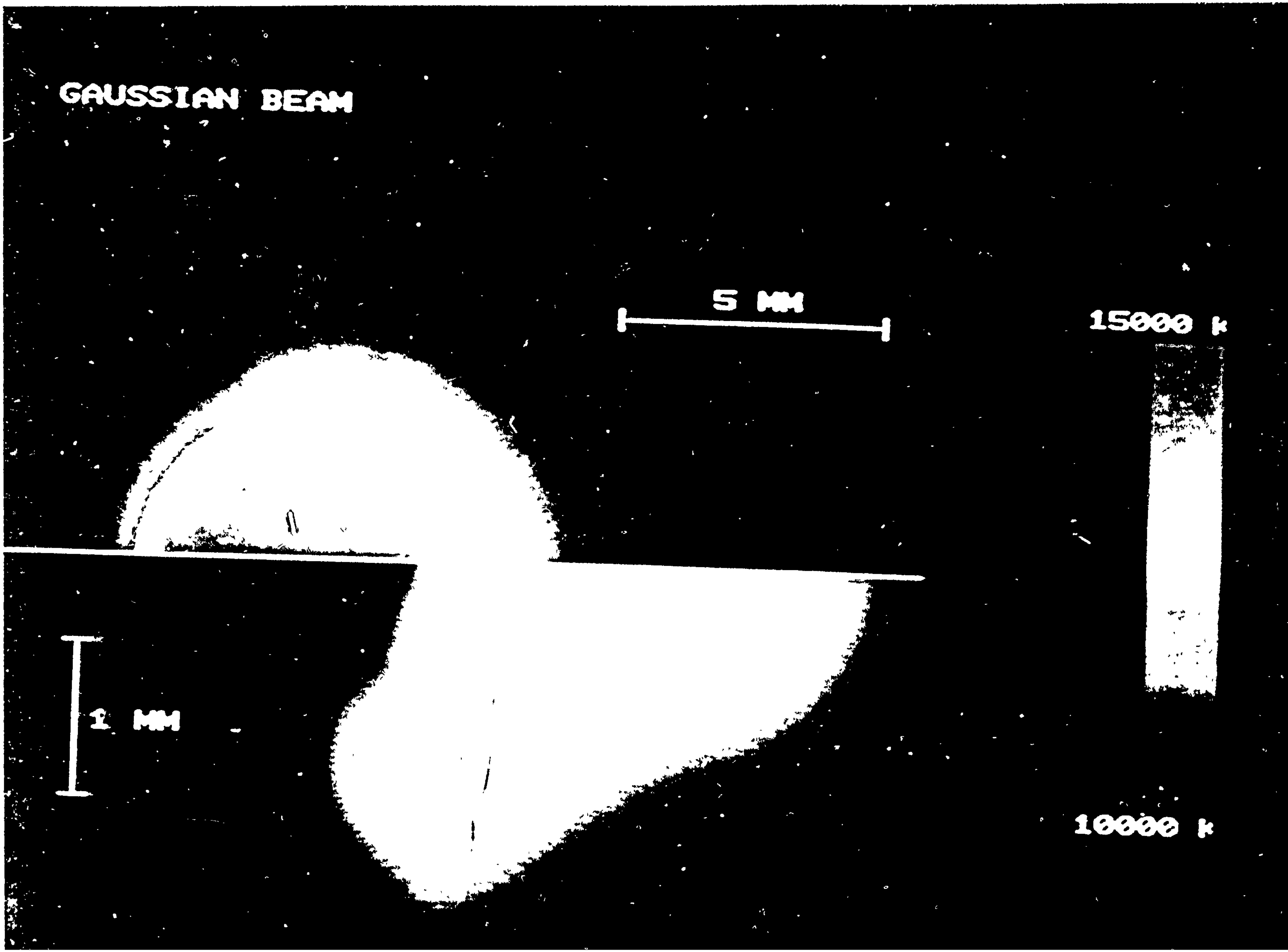

GAUSSIAN
ANNULAR
INTENSITY [10^4 W/cm^2]
1.5
1.0
0.5
0.0
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
RADIAL DISTANCE [mm]



GAUSSIAN
ANNULAR
INTENSITY [10^2 W/cm^2]
1.5
1.0
0.5
0.0
16
17
18
19
20
21
AXIAL DISTANCE [cm]



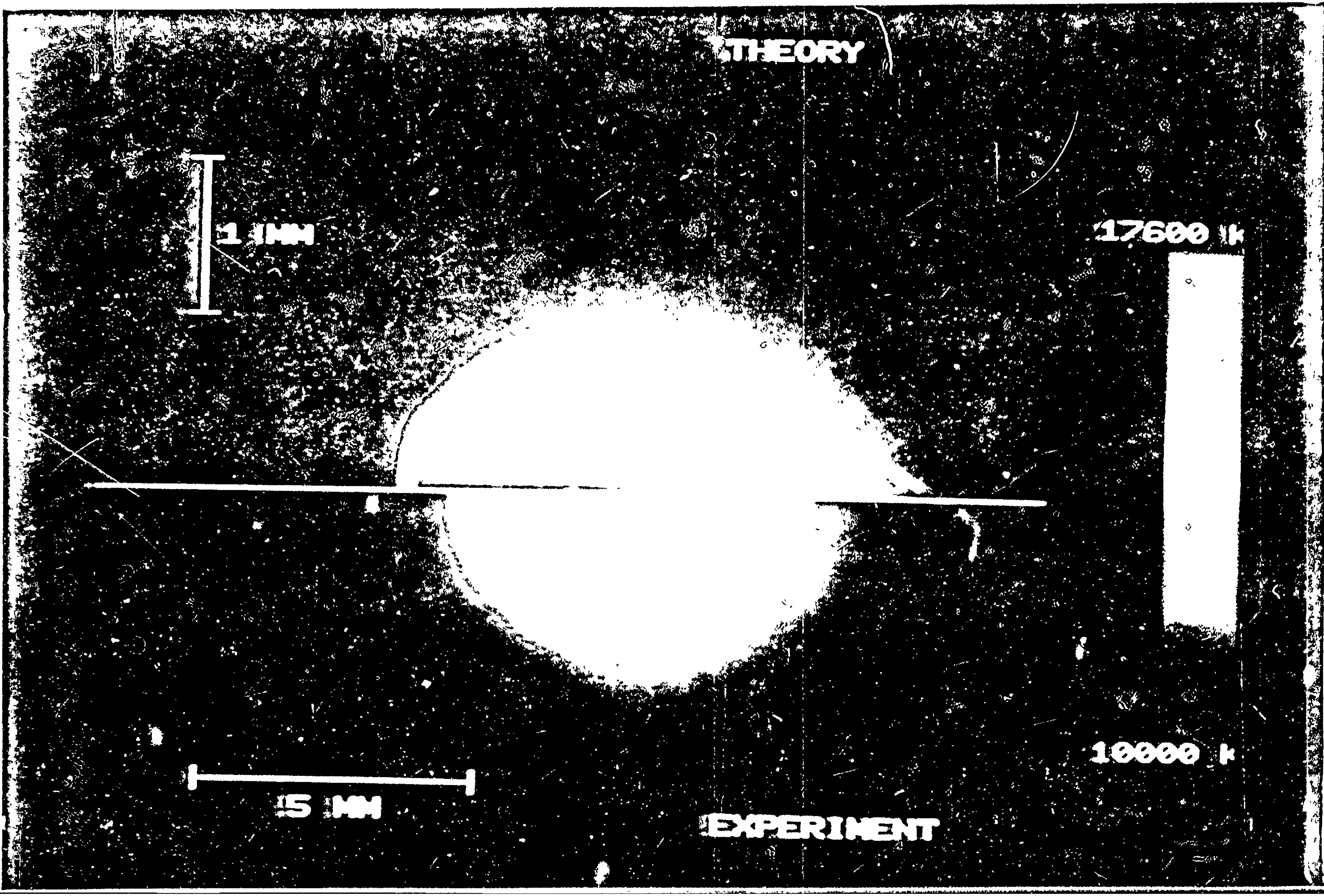
FRACTION OF INCIDENT POWER
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
FLOW SPEED [m/sec]
— Absorption, Annular
— Absorption, Gaussian
— Radiation, Annular
— Radiation, Gaussian

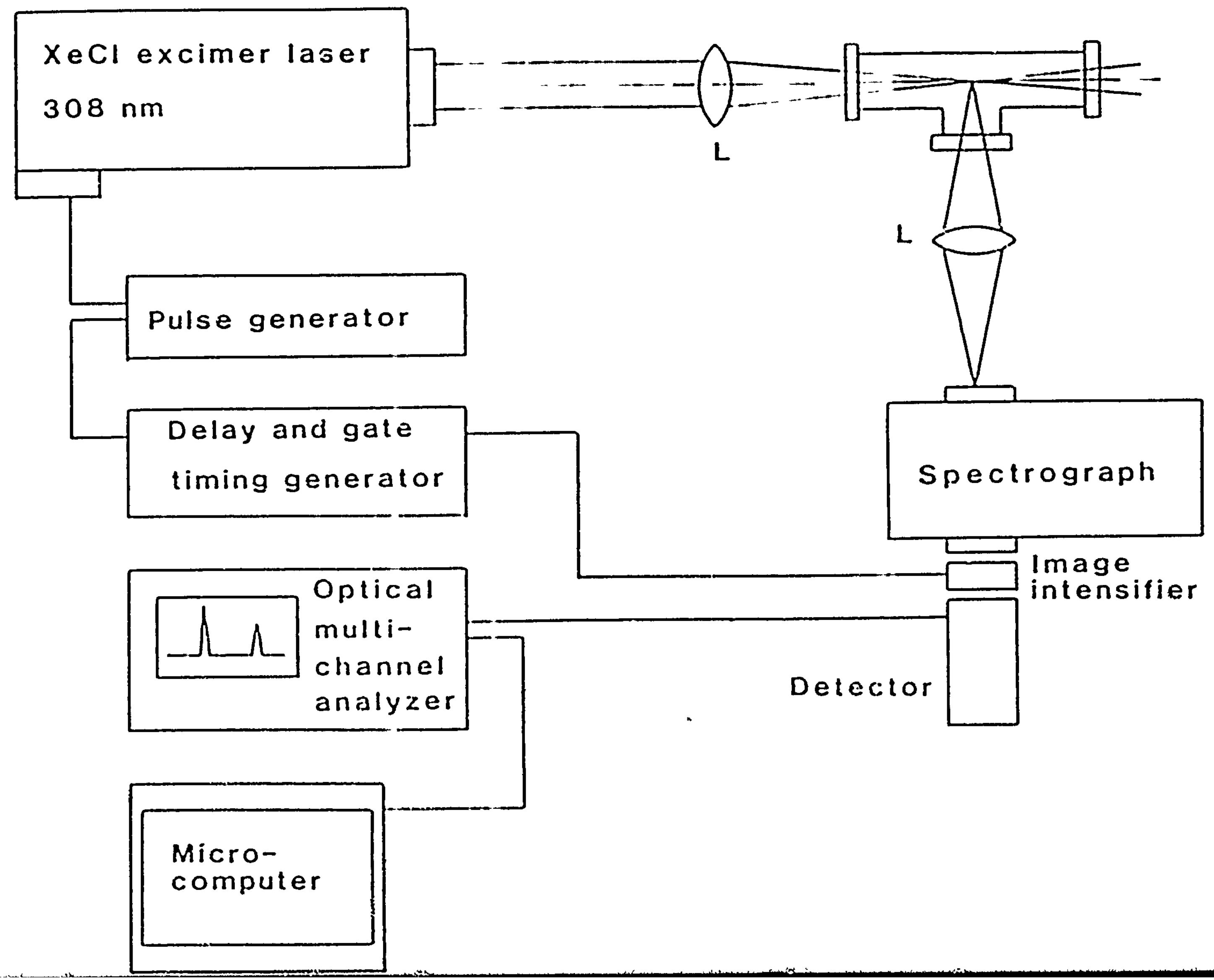

GAUSSIAN BEAM
5 MM
15000 K
1 MM
10000 K

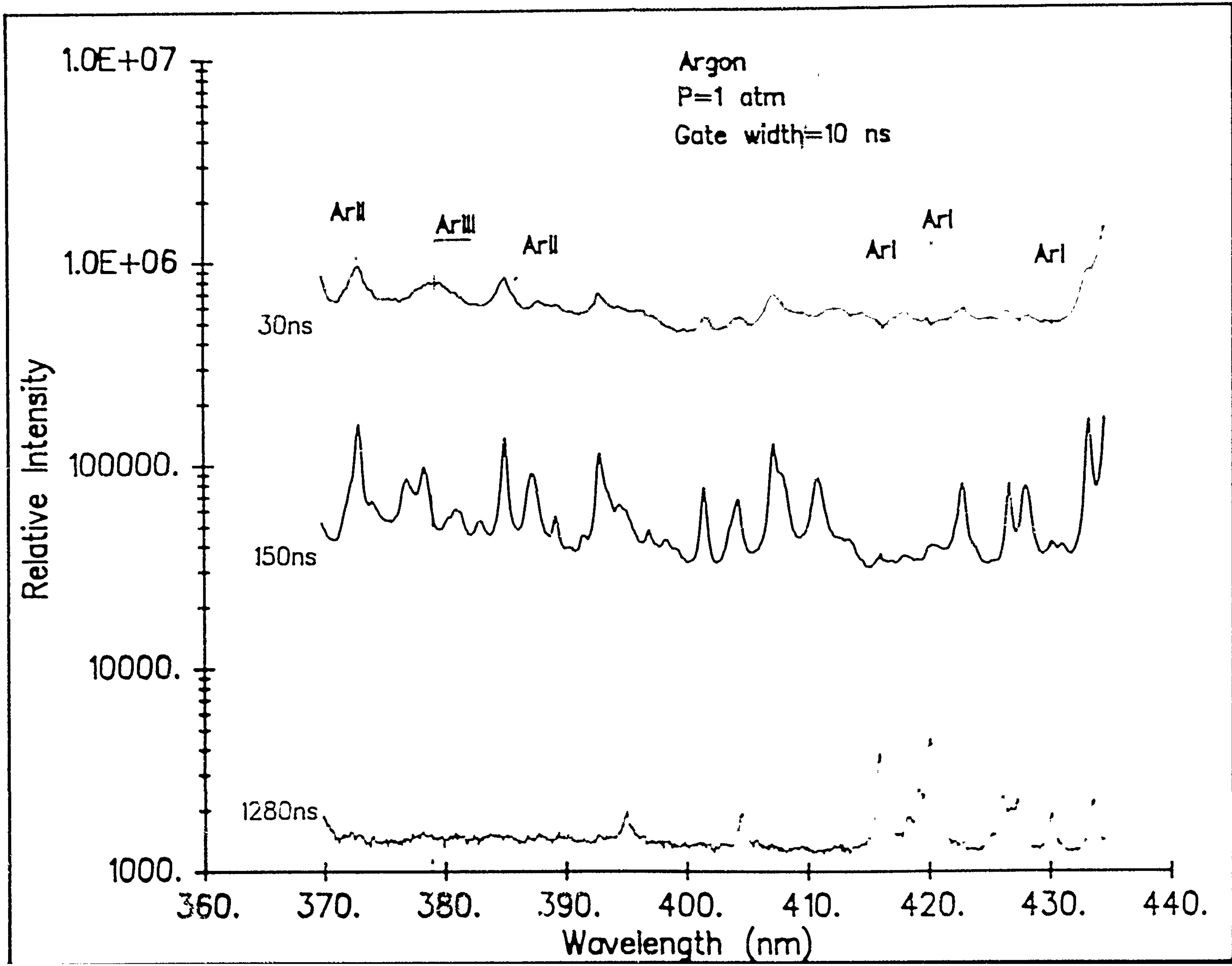
UTSI / LANL Experiments

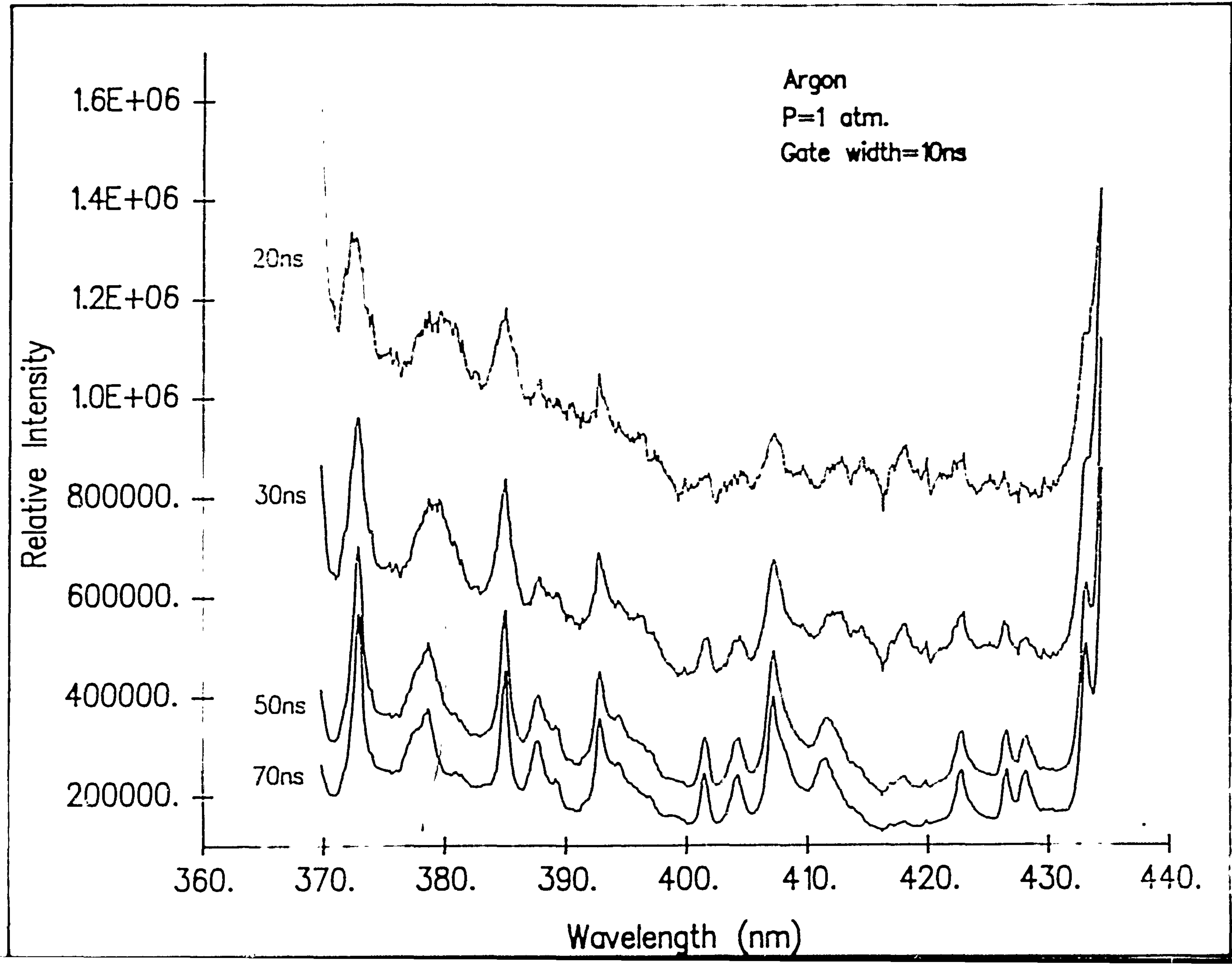
- Can Quasi-Steady-State be Established
- Effect of Micropulses on Fractional Absorption
- Temporal Characteristics of Plasma Temperature
- Non-Equilibrium Effects

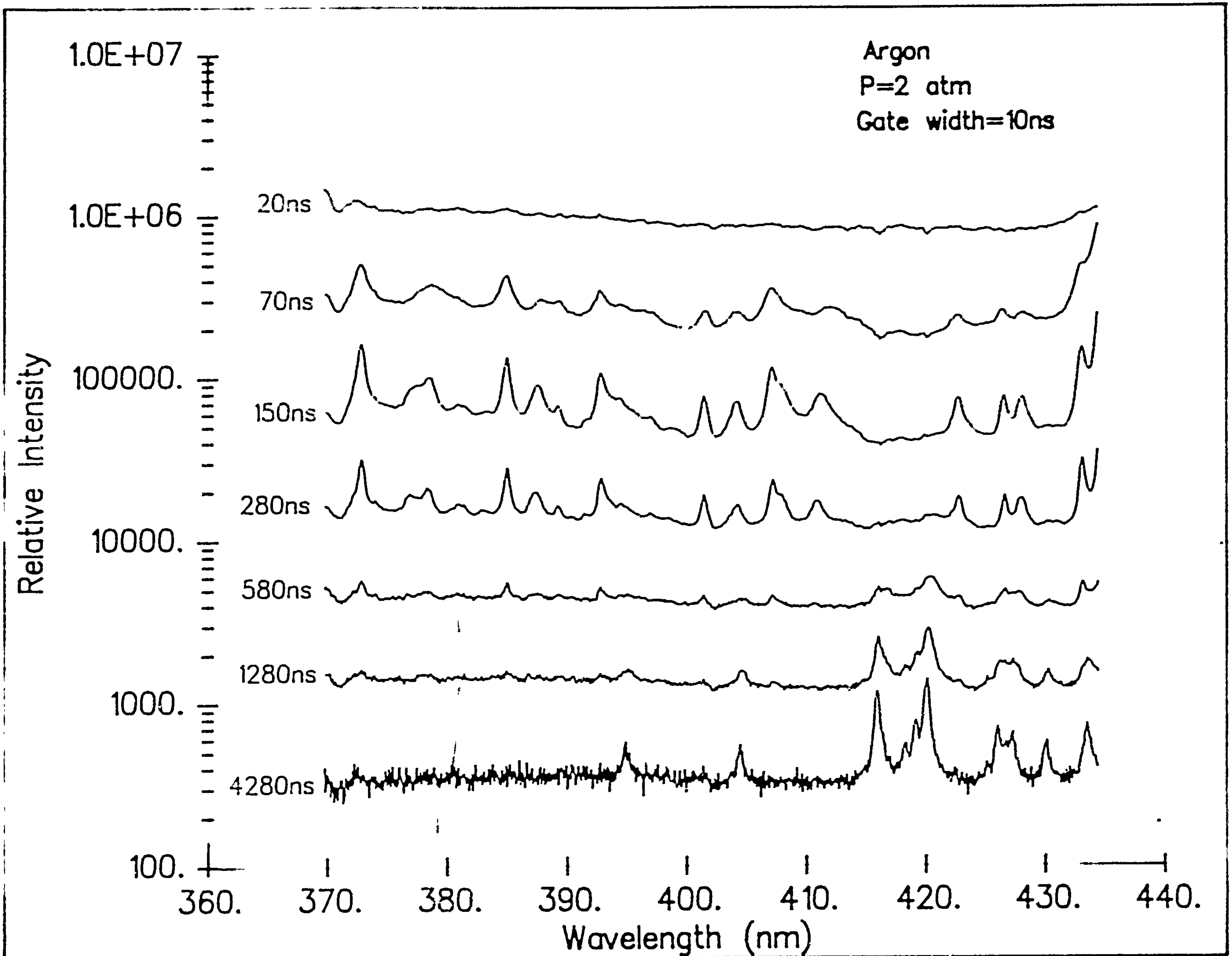
GL-0701

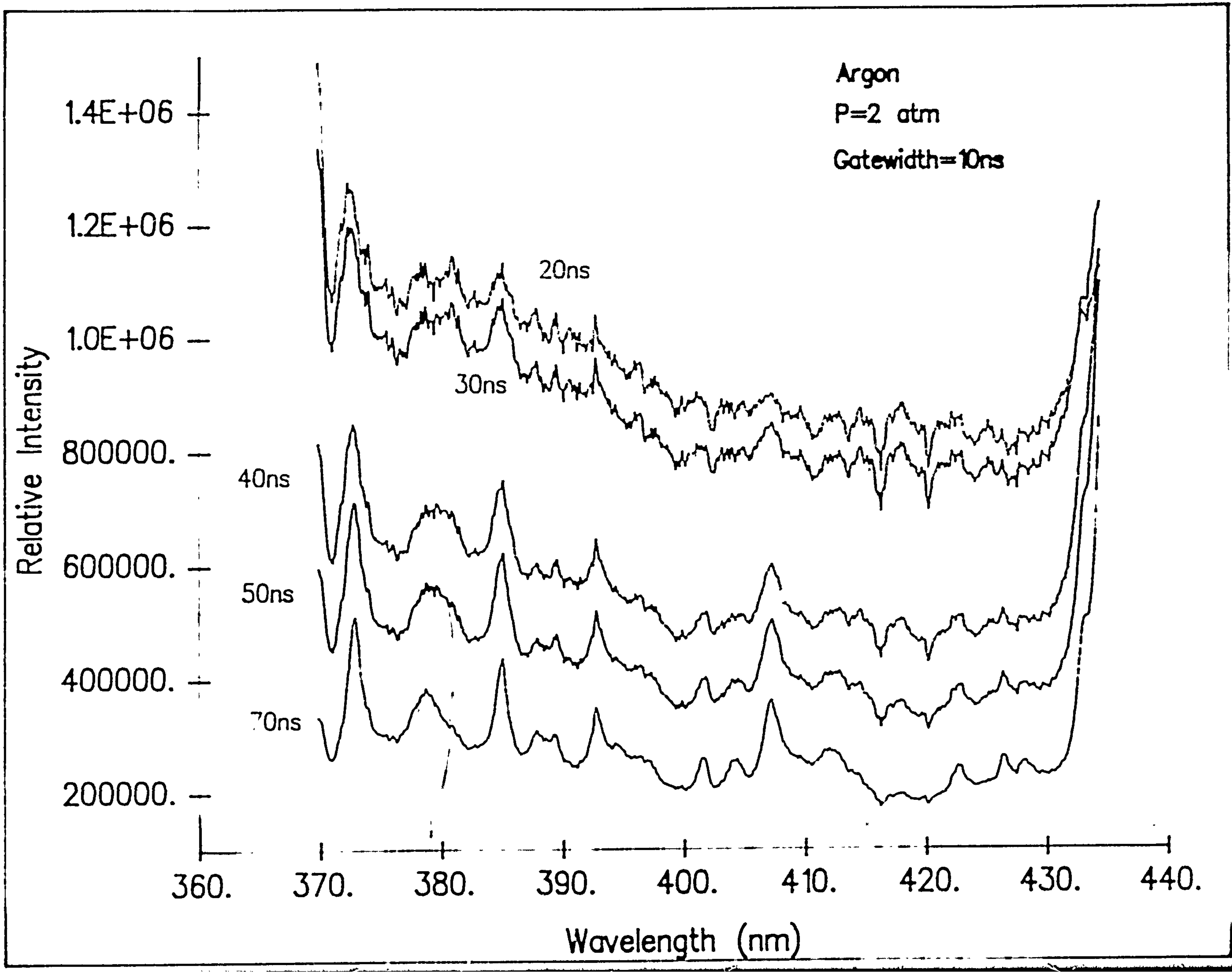

THEORY
1 MM
17600 K
10000 K
5 MM
EXPERIMENT

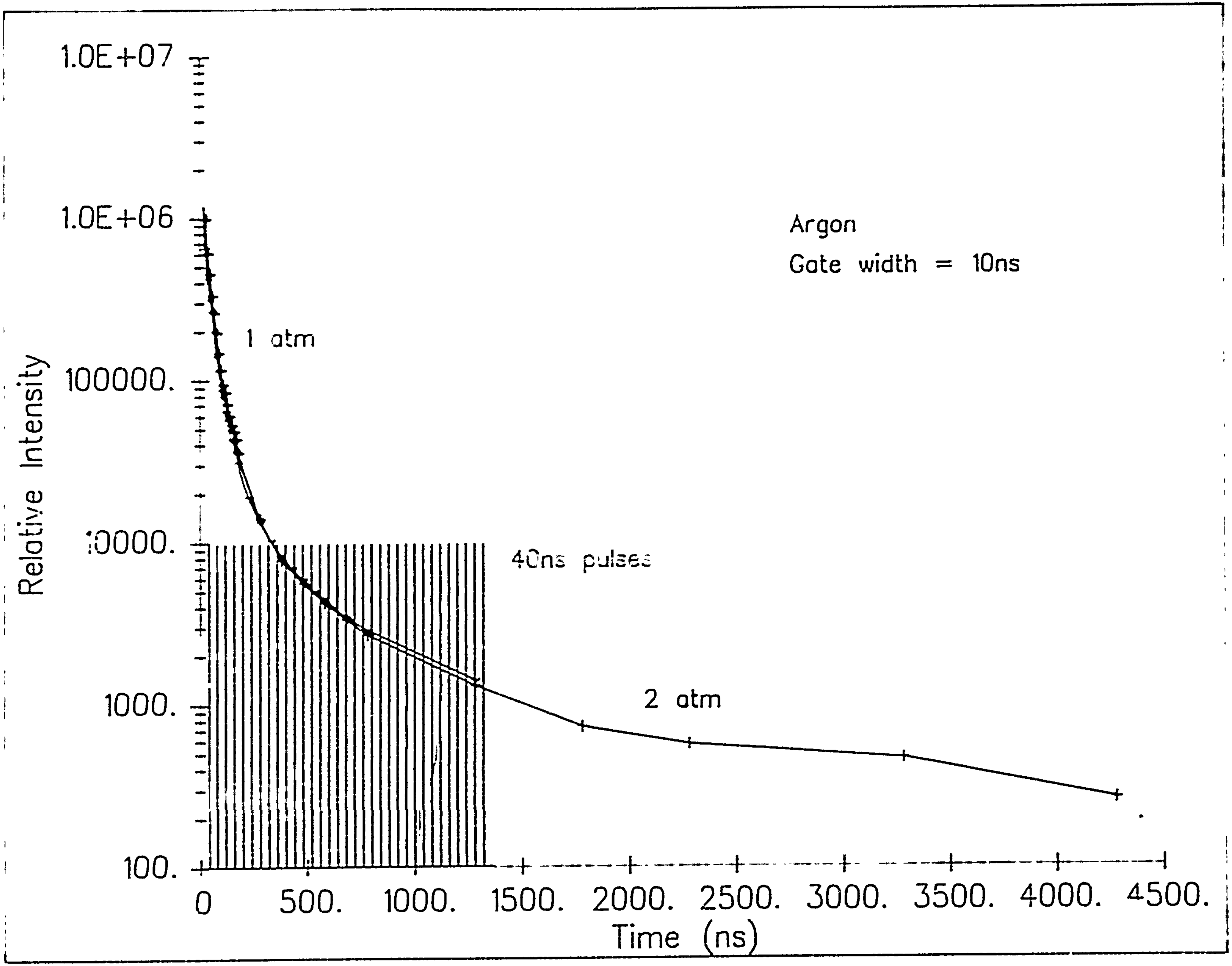

XeCl excimer laser
308 nm
L
L
Pulse generator
Delay and gate
timing generator
Spectrograph
Image
intensifier
Optical
multi-
channel
analyzer
Detector
Micro-
computer


Argon
P=1 atm
Gate width=10 ns
ArII
ArIII
ArII
ArI
ArI
ArI
30ns
150ns
1280ns
1.0E+07
1.0E+06
100000.
10000.
1000.
Relative Intensity
360.
370.
380.
390.
400.
410.
420.
430.
440.
Wavelength (nm)


Argon
P=1 atm.
Gate width=10ns
20ns
30ns
50ns
70ns
Relative Intensity
1.6E+06
1.4E+06
1.2E+06
1.0E+06
800000.
600000.
400000.
200000.
360.
370.
380.
390.
400.
410.
420.
430.
440.
Wavelength (nm)

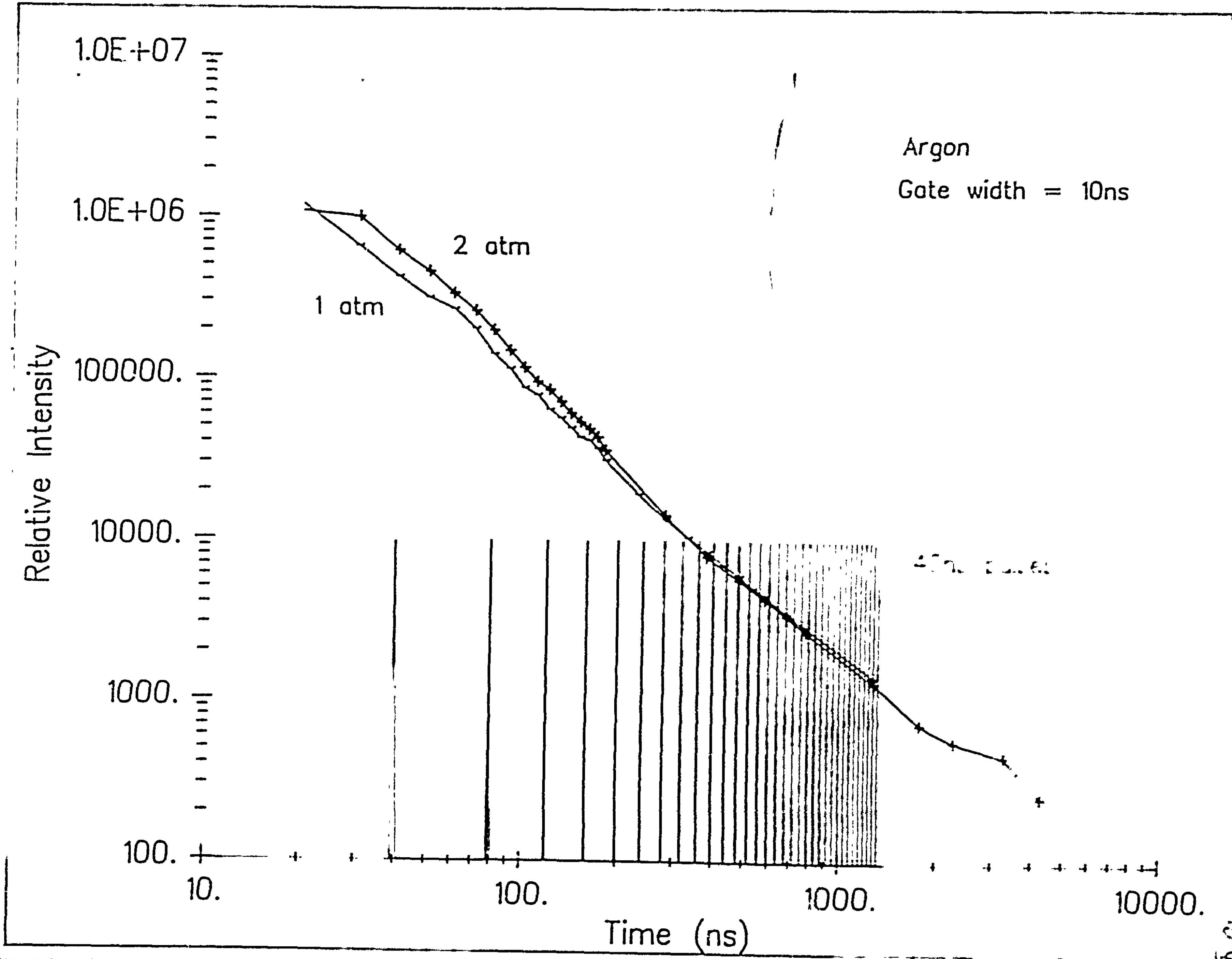

Argon
P=2 atm
Gate width=10ns
Relative Intensity
1.0E+07
1.0E+06
100000.
10000.
1000.
100.
20ns
70ns
150ns
280ns
580ns
1280ns
4280ns
360.
370.
380.
390.
400.
410.
420.
430.
440.
Wavelength (nm)


Argon
P=2 atm
Gatewidth=10ns
20ns
30ns
40ns
50ns
70ns
Relative Intensity
1.4E+06
1.2E+06
1.0E+06
800000.
600000.
400000.
200000.
360.
370.
380.
390.
400.
410.
420.
430.
440.
Wavelength (nm)



1.0E+07
1.0E+06
100000.
10000.
1000.
100.
Relative Intensity
0
500.
1000.
1500.
2000.
2500.
3000.
3500.
4000.
4500.
Time (ns)
Argon
Gate width = 10ns
1 atm
40ns pulses
2 atm

121



Argon
Gate width = 10ns
2 atm
1 atm
Relative Intensity
1.0E+07
1.0E+06
100000.
10000.
1000.
100.
10.
100.
1000.
10000.
Time (ns)

Current Research Status

- Plasma is Stable in Forced Convective Flow
- Required Fractional Absorption can be Obtained
- Conversion Efficiency can be Controlled with Flow
- Excellent Predictive Capability
- Wavelength Scaling Appears Favorable
- Characteristics using Pulsed Format - UnKnown
- Radiative Transport Scaling - UnKnown

GL-0697

ABSTRACT

FUNDAMENTALS OF CW LASER PROPULSION

Prepared by

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Work Supported by AFOSR
under
Grant No. 88-0129
(Dr. Mitat Birkan is Program Manager)

Overview

The key scientific issue for laser rocket propulsion using continuous laser beams is gas heating by laser supported plasmas. Cold gases do not absorb the laser energy at wavelengths of current interest (1 μ to 11 μ). Only by sustaining an intense plasma, at fluxes of the order of 10^6 watts/cm^2, can the laser energy be absorbed via inverse bremsstrahlung and some molecular band absorption. Such laser supported plasmas (LSP) form near the focus of a converging high-power laser beam, and have been found to be stable under a wide range of power, pressure, beam-convergent f/no.'s and flow velocities.

Temperatures within the plasma core are extremely high (approaching 20,000 K), meaning that the core is highly ionized and able to strongly absorb the laser energy, as mentioned, through inverse bremsstrahlung continuum absorption. Unfortunately, the very high temperatures also tend to lead to significant radiation losses from the plasma, particularly in the visible and UV spectrum.

Thus, the key to the problem is maximizing the laser energy absorption by the plasma, while at the same time minimizing radiation losses to the chamber walls. In this way, the fractional retention of the laser energy by the propellant gas (i.e., the thermal conversion efficiency) is optimized.

In order to achieve this objective, the fundamental behavior of properties of LSP's must be studied under a wide range of conditions. Of particular interest are plasma core temperature distributions, plasma size and stability information, absorption fractions, radiation losses, characterization of the flowfield around the LSP, and most importantly, measurements of the thermal conversion efficiency. Laser-sustained plasmas have been studied for over a decade, but only a few investigations have been performed with the application of propulsion in mind (i.e., operation in forced-convective flow regimes).

University of Illinois Studies

The primary purpose of ongoing research at the University of Illinois is to provide fundamental measurements of both the local and global properties of laser-sustained plasmas in flowing argon, (a substitute for H_2) so that the feasibility of laser propulsion may be accurately assessed. As mentioned above, properties of particular interest include plasma temperature fields, stability and initiation information, global absorption fractions, and thermal efficiencies.

The laser employed in the experiments is an Avco-Everett, Model HPL 10 CW CO_2 laser capable of sustained 10 kW beam output at 10.6 microns. The beam axial cross-section is annular with a Gaussian energy distribution over the radial cross-section. To facilitate materials processing (the laser's primary function), the annular beam has been expanded to a diameter of 2.6 inches.

Laser sustained plasmas are created by focusing the laser inside a cylindrical absorption/flow chamber shown in Fig. 1. The chamber is placed vertically at the test stand to preserve internal axial flow symmetry in the presence of strong buoyancy effects. The chamber, attachment flanges, various ports and feed-throughs, and window assemblies were machined from 304 stainless steel. Stainless steel was chosen for its strength and corrosive resistance. A 5-in. ID was selected to allow complete studies of thermal mixing in the flowfield.

Plasmas are initiated by focusing a 10 kW CW CO_2 laser inside a pressurized flow vessel through a sodium chloride window. The f/no. of the focusing optics can be varied from f/2.2 to f/8, and the pressure and flow rate of the argon gas can be varied widely. Actual plasma initiation is achieved by inserting retractable zinc or tungsten targets at the laser focus.

Emissions from the plasma are used to spectroscopically measure temperatures within the plasma core, using an OMA-3 spectroscopic system. The laser energy that is transmitted through the plasma is collected and measured by a copper-cone calorimeter mounted above the chamber. Temperature distributions in areas downstream from the plasma are measured using a movable grid of high-temperature thermocouples. These measurements can then be used to assess flow patterns within the chamber, and to determine thermal conversion efficiencies. A laser-induced fluorescence diagnostic system is also being used in an effort to obtain more accurate instantaneous temperature mappings of the downstream flow regions, as well as for qualitative visualization of flow patterns near the plasma.

References [1] through [4] provide descriptions of the work performed to date with these facilities.

Important Conclusions

Laser-sustained plasmas have been initiated and maintained in pressurized flowing argon under a wide range of flow and power conditions. The plasmas tend to be highly stable energy conversion mechanisms, but can be forced to extinguish through either a reduction in power or an increase in flow velocity.

Spectroscopic temperature scans of the plasma have been used to study the size, shape, and behavior of the LSP under different power and flow conditions. These temperature fields have subsequently been used to calculate absorption fractions and thermal efficiencies, and have been shown to agree well with out other independent measurement techniques. Also, it has been shown that local thermodynamic equilibrium exists within the plasma core.

Global absorption fractions have been measured under different conditions, with fractions as high as 80 percent being typical. Increasing absorption with laser power is indicated, a trend that becomes more pronounced when the f number of the focusing optics is increased.

Thermal efficiencies have been measured under a range of conditions using a grid of thermocouples. Values as high as 40 percent have been recorded. It has been found that efficiency tends to decrease with laser power, but to increase with flow velocity (until a peak value is reached and blowout subsequently occurs).

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3. Glumb, R. J., "Experimental and Theoretical Studies of Laser-Sustained Argon Plasmas for Rocket Propulsion," Ph.D Thesis, University of Illinois, Department of Mechanical and Industrial Engineering (1986).

4. Mazumder, J., Rockstroh, T. J., and Krier, H., "Spectroscopic Studies of Plasmas during CW Laser Gas Heating in Flowing Argon," J. Applied Physics, Vol. 62, No. 12, pp. 4712-4718 (1987).

February 22, 1988

Accompanying Text for Workshop Figures

Figure 1

Schematic of the current experimental test stand. Of particular interest are the precision optical mounts which carry the two lower copper mirrors, the translating stage which positions the focusing lens, the sintered steel flow straightener, and the converging quartz section.

Figure 2

Detailed schematic of the laser absorption chamber shown also in Figure 1. As originally designed the 24 gas inlet holes created flow turbulence which resulted in plasma instability at flow velocities approaching 2 m/s. Currently a sintered steel flow straightener quiets the flow substantially, allowing for stable plasmas at much higher flow velocities. The converging quartz section shown accelerates the flow to almost 10 m/s at 28.1 g/s. Other sections can be used which speed up the flow even more.

Figure 3

In addition to improvements to the gas inlet system, two successive laser beam alignments have been performed which also increased the stability of plasmas at higher flow velocities. The effect of these changes on the velocity at which a plasma becomes unstable is seen in this figure. These curves are for plasmas sustained with an f/4 focusing geometry. We were unable to extinguish an f/4 plasma at 1.5 kW with our maximum flow capability. No curve has yet ben produced for f/7 plasmas, but they have been shown to be less stable than f/4 plasmas. It is because of these improvements to the test facility that new operating conditions can be explored and compared to theoretical predictions.

Figure 4

Results of high velocity experiments with f/7 focusing optics and 1 atmosphere argon pressure. As seen in previous work, there is an upward trend in efficiency with the increasing argon mass flux (g/sm^2), made possible by the converging section. High flow velocity (i.e. mass flux) indicates a cooler overall plasma with less radiation loss. The figure shows that a higher power plasma achieves an efficiency comparable to a lower power plasma only at a higher mass flux.It appears that a 5 kW plasma is at an ill-matched operating condition. Figure 5 shows that a 5 kW plasma has a higher global absorption fraction than a 2.5 kW plasma, and

therefore has the potential for a higher thermal conversion efficiency. Higher velocity experiments must be performed to map out the behavior of a series of experiments such as that shown here, in an effort to optimize the operating conditions at high power. These trends will become important when a mass flux is required for a certain application that is beyond the blowout mass flux of a given lower power plasma.

Figure 5

Shows that higher input laser power results in higher global absorption fractions. It appears that a 5 kW plasma requires a higher mass flux to achieve its peak absorption than due the lower power plasmas. This is because a higher power plasma will stabilize further upstream of the laser focus at a given mass flux, which is a characteristic of ill-matched operating conditions. Because efficiency is still on the rise at these mass flows (Figure 4), it appears that there is a strong radiative dependence on flow velocity as well.

Figure 6

Compares measured efficiency using two flow configurations. All the points below 200 cm/s are data taken without a converging section in the chamber, and the points above 200 cm/s are with a converging section. The obvious discontinuity in the data is probably due to significantly higher heat losses from the exhaust gas when using the converging section. More than seven times less mass flow-rate (g/s) is required to achieve a given velocity with this converging section than without, resulting in temperature increases seven times greater if equal efficiency is to be realized (i.e. no discontinuity). If one assumes that this required temperature rise is realized, then one will see that heat losses dependent upon temperature difference with the surroundings (i.e convection and radiation to the cold chamber walls), will be increased. What is measured with our thermocouple diagnostics is the temperature after the above heat losses have taken place, giving the appearance of dramatically lower efficiency. If the above discussion is a valid explanation of the discontinuity, then efficiencies approaching 50% are evidenced.

Figure 7

Shows the effect of increasing the chamber gas pressure on global absorption for plasmas at constant mass flux (g/sm^2). As pressure increases the plasma shifts further upstream of the focus due to an increase in absorption coefficient. However, the shift into a lower intensity region of the beam, along with a significant decrease in size of the plasma results in a decrease in overall absorption fraction. Better matching of the mass flux with power and high pressure should result in global absorption fractions at least as high as for

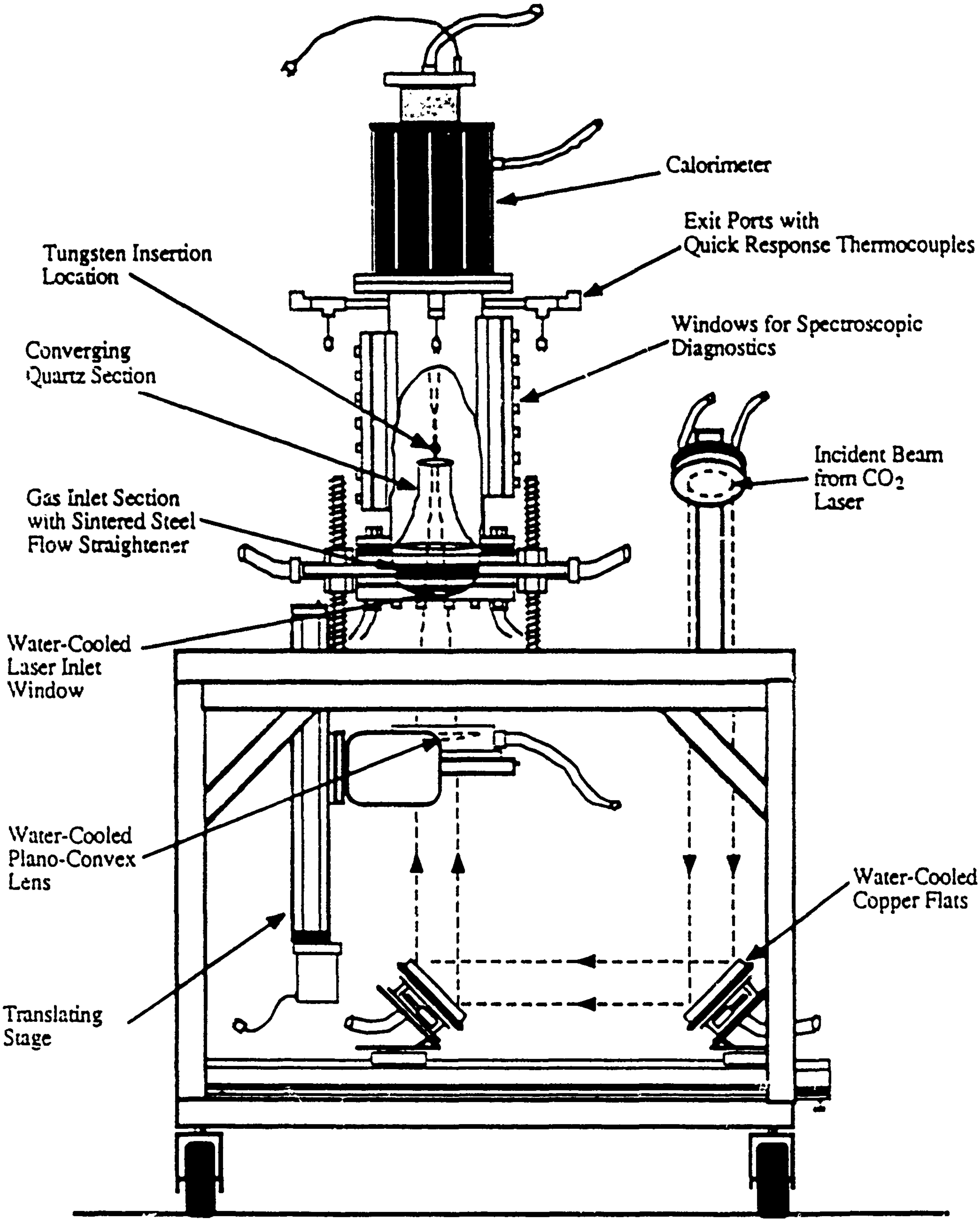
plasmas at atmospheric pressure. Running experiments with elevated pressure and with double or triple the present mass flux range should help answer this questions.

Figure 8

Shows the resultant decrease in thermal efficiency with increasing pressure at constant mass flux. The decrease in global absorption coupled with an increase of radiative emission coefficient with gas pressure cuts the thermal conversion fraction significantly. Experiments at elevated mass flux will be helpful in understanding the relationship between operating conditions and the various energy conversion fractions.

Figure 9

Shows that at a given power plasma at elevated pressure, global absorption is increasing with increasing mass flux. This appears to be a result of pushing the plasma closer to the focus, representing a better matched set of operating conditions. Once again, even higher mass fluxes should be used in an attempt to optimize the plasma energy conversion operating conditions.



Calorimeter
Exit Ports with
Quick Response Thermocouples
Tungsten Insertion
Location
Windows for Spectroscopic
Diagnostics
Converging
Quartz Section
Incident Beam
from CO_2
Laser
Gas Inlet Section
with Sintered Steel
Flow Straightener
Water-Cooled
Laser Inlet
Window
Water-Cooled
Plano-Convex
Lens
Water-Cooled
Copper Flats
Translating
Stage

Figure 1

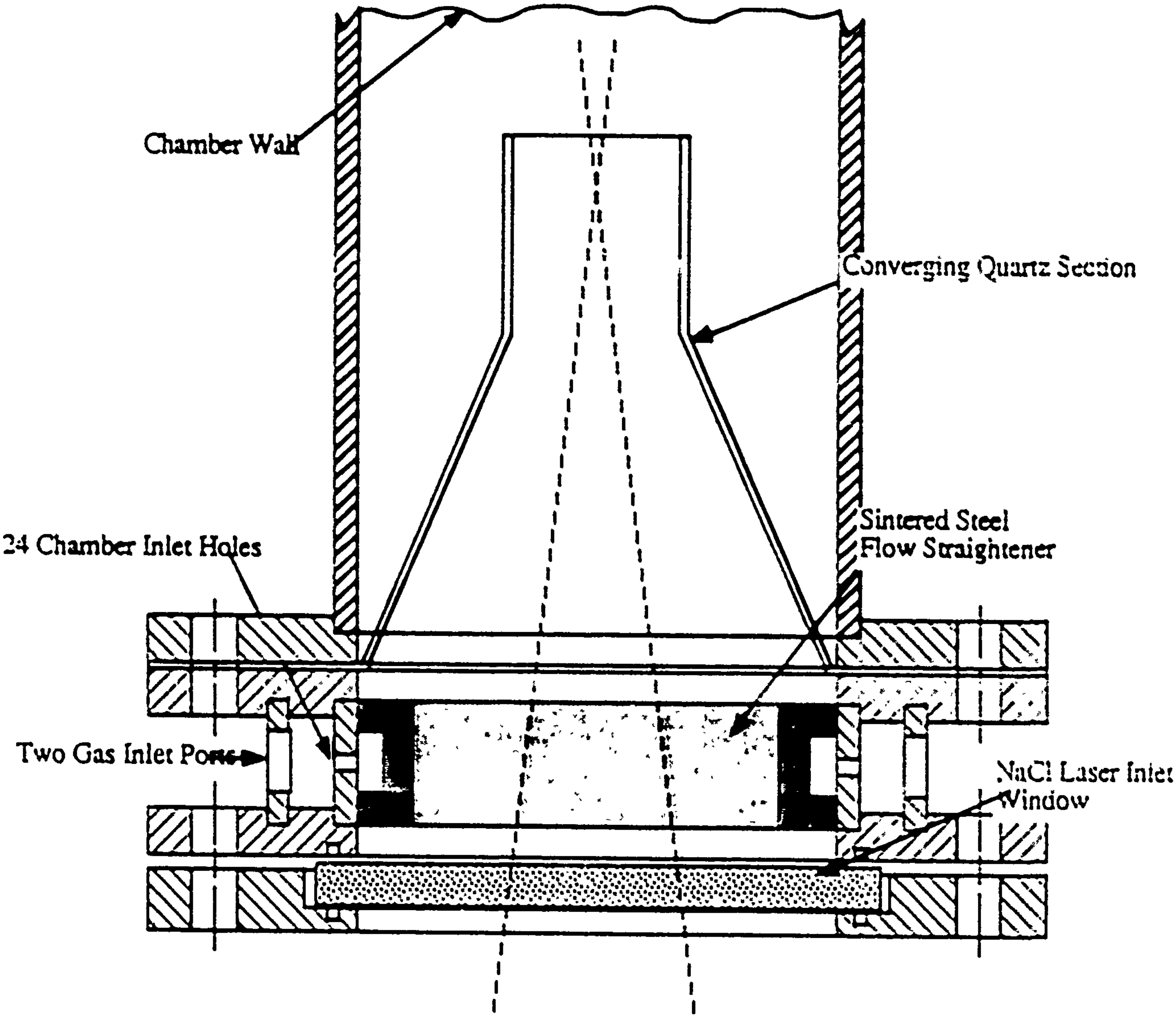
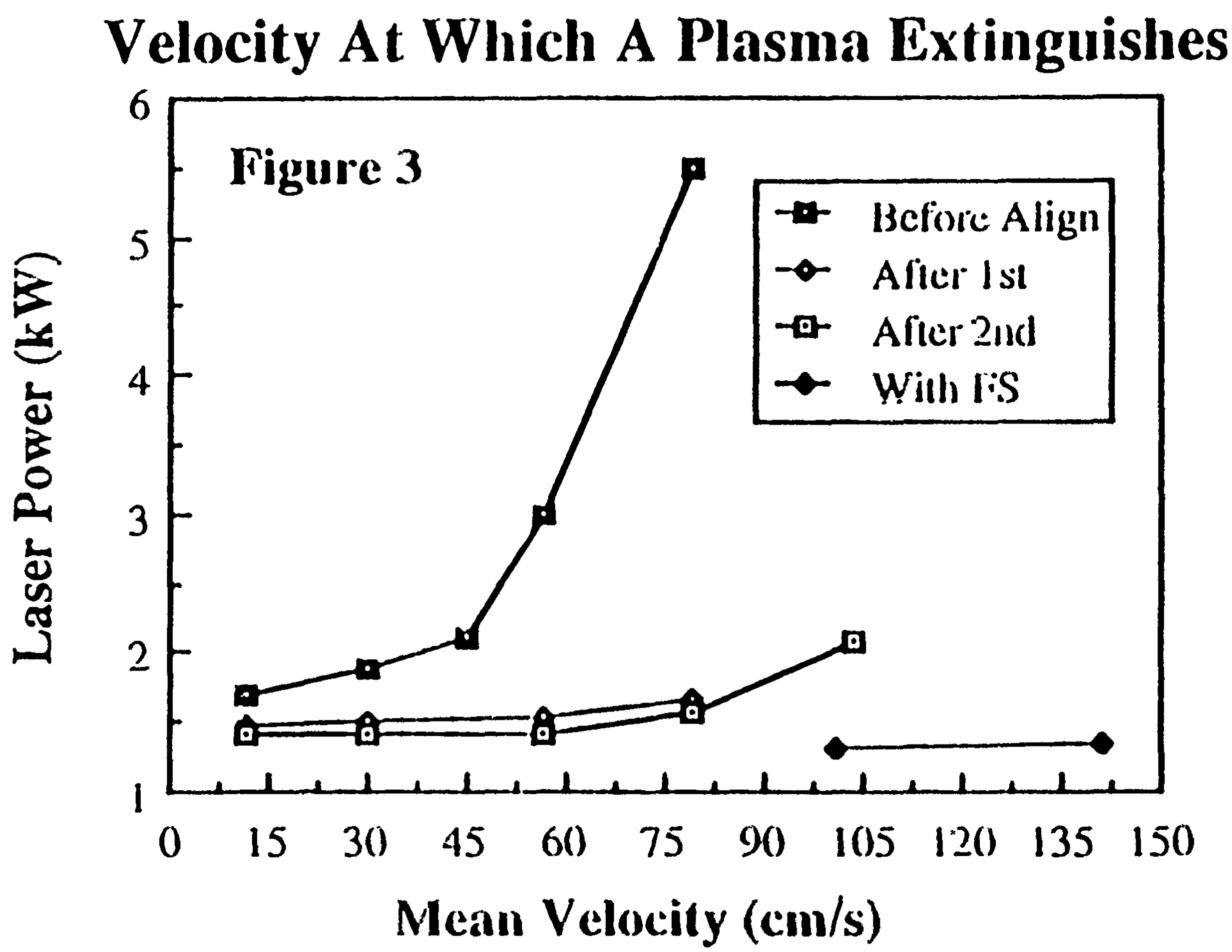

Chamber Wall
Converging Quartz Section
24 Chamber Inlet Holes
Sintered Steel
Flow Straightener
Two Gas Inlet Ports
NaCl Laser Inlet
Window

Figure 2


Velocity At Which A Plasma Extinguishes
Figure 3
Before Align
After 1st
After 2nd
With FS
Laser Power (kW)
1
2
3
4
5
6
0
15
30
45
60
75
90
105
120
135
150
Mean Velocity (cm/s)

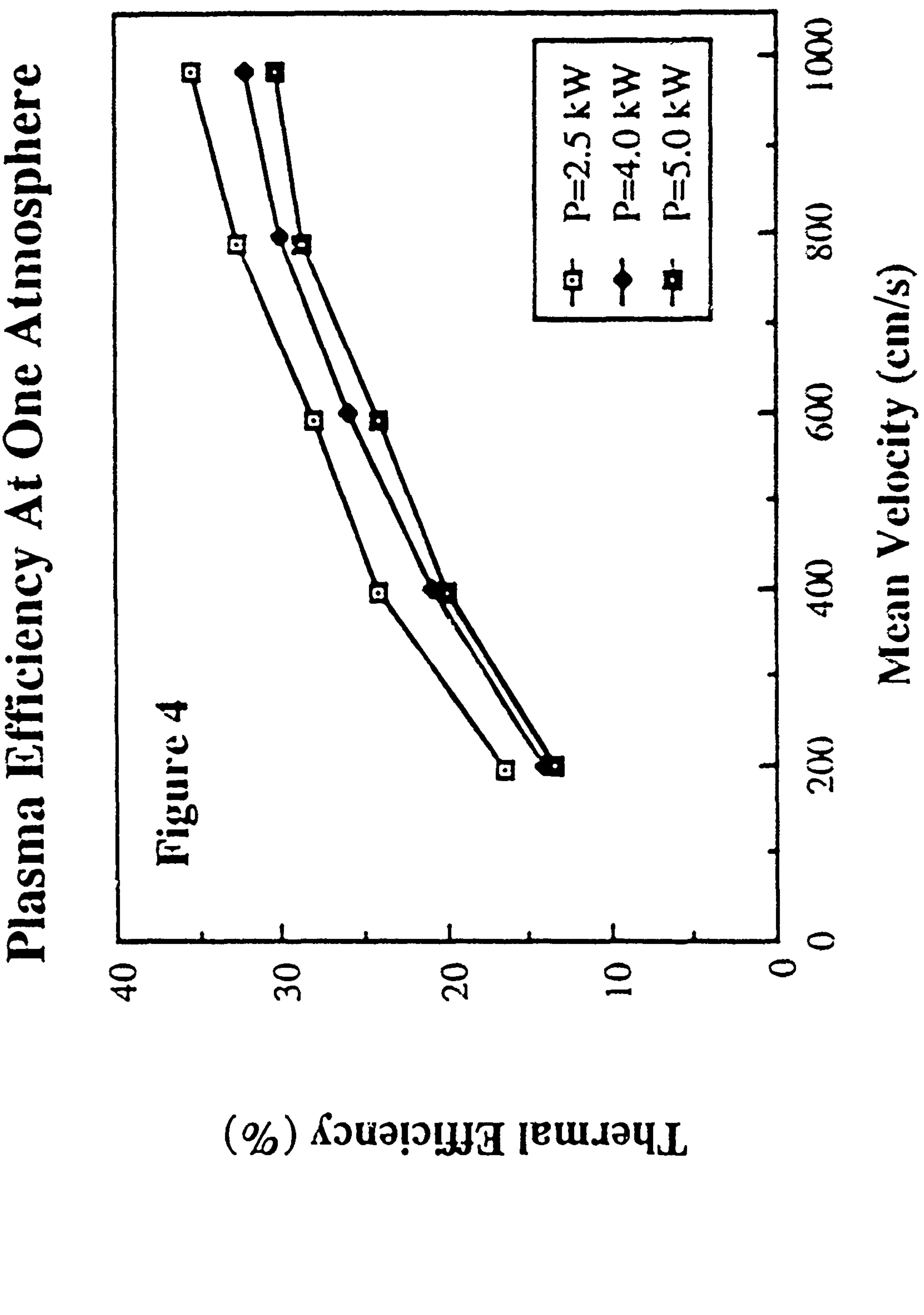

Plasma Efficiency At One Atmosphere
Figure 4
Thermal Efficiency (%)
40
30
20
10
0
0
200
400
600
800
1000
Mean Velocity (cm/s)
P=2.5 kW
P=4.0 kW
P=5.0 kW

Figure 4

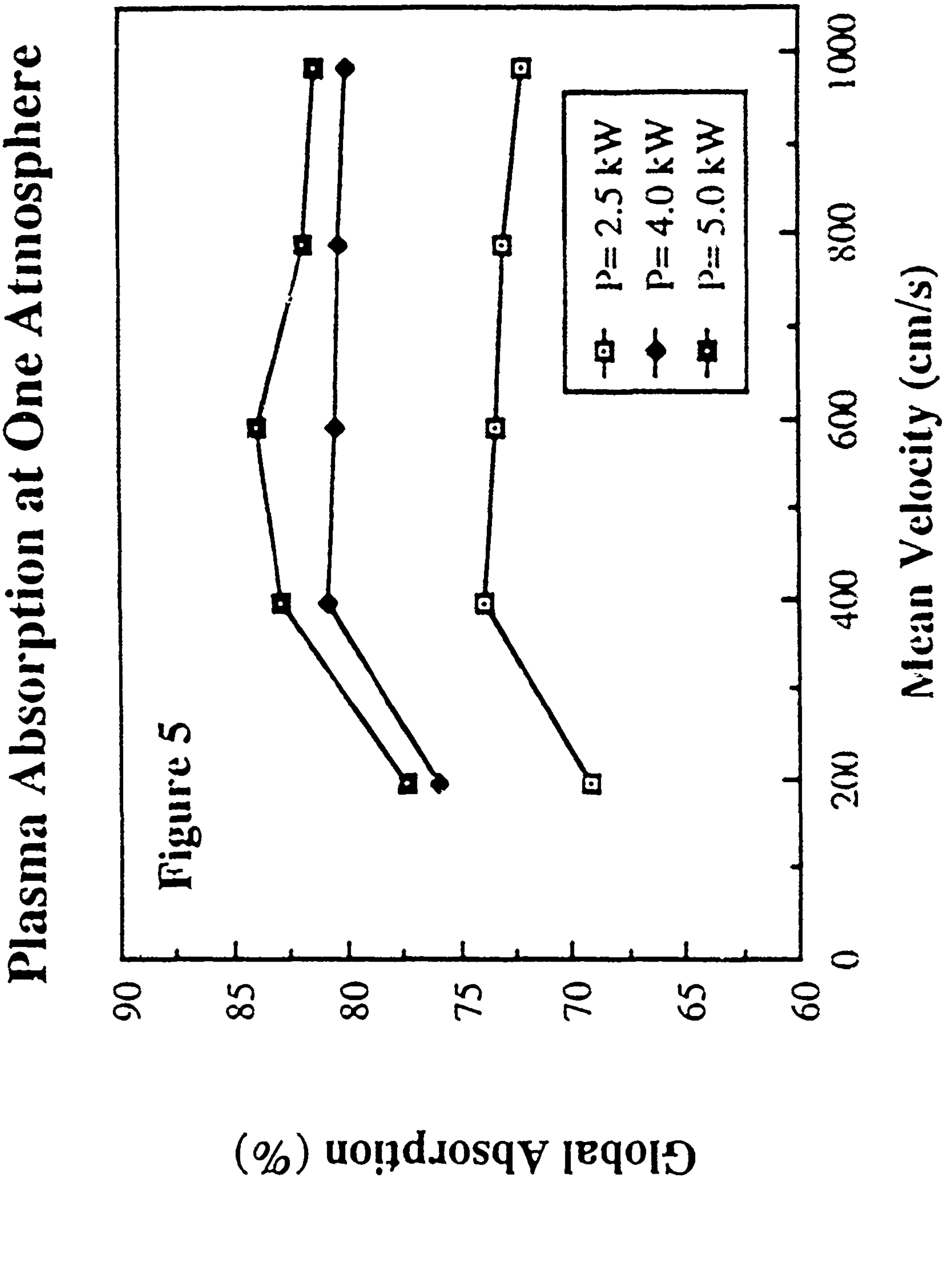
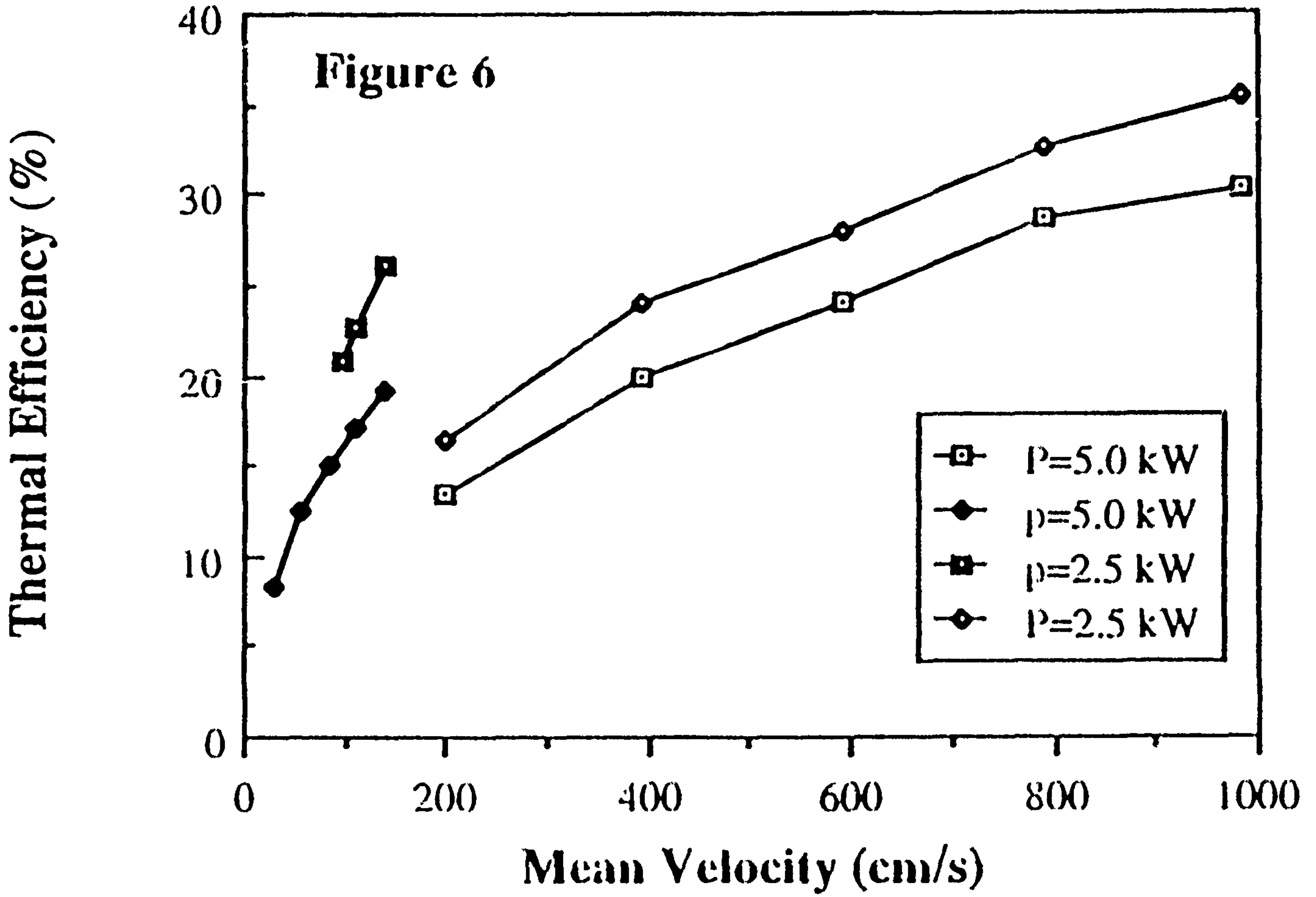
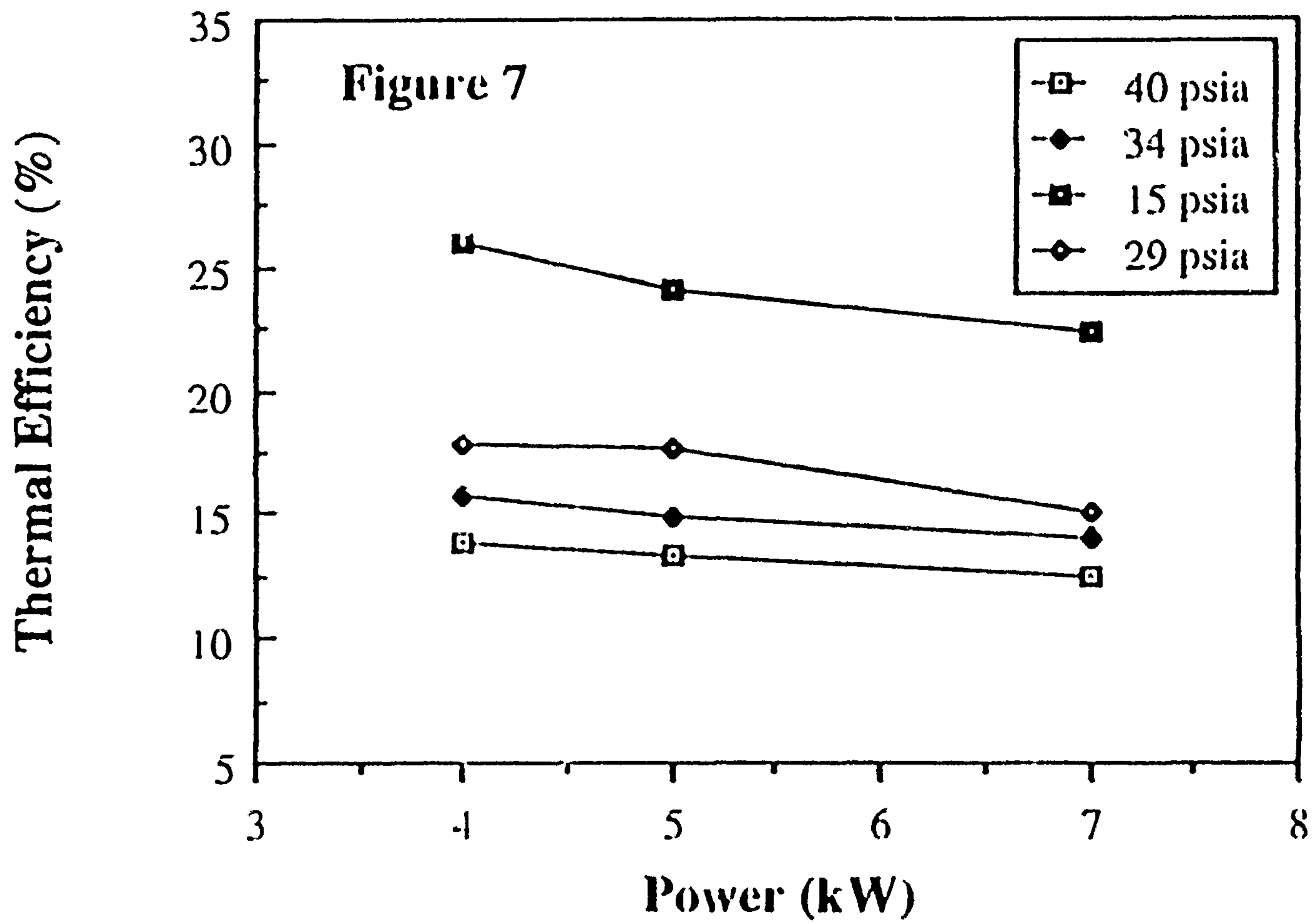

Plasma Absorption at One Atmosphere
Figure 5
Global Absorption (%)
90
85
80
75
70
65
60
0
200
400
600
800
1000
Mean Velocity (cm/s)
P= 2.5 kW
P= 4.0 kW
P= 5.0 kW

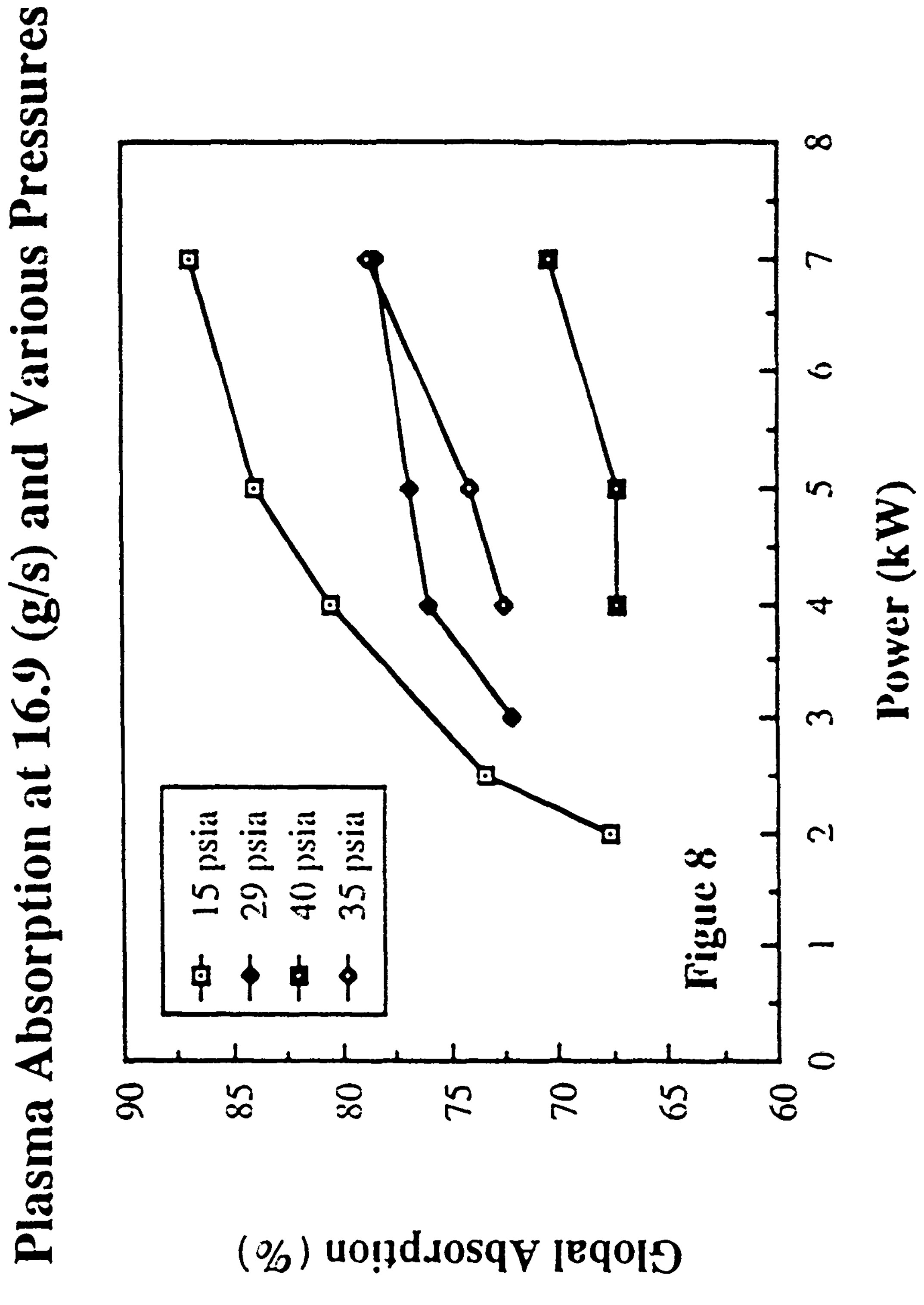
Figure 5

Measured Efficency at Two Different Flow Configurations



Plasma Efficiency at 16.9 (g/s) and Various Pressures

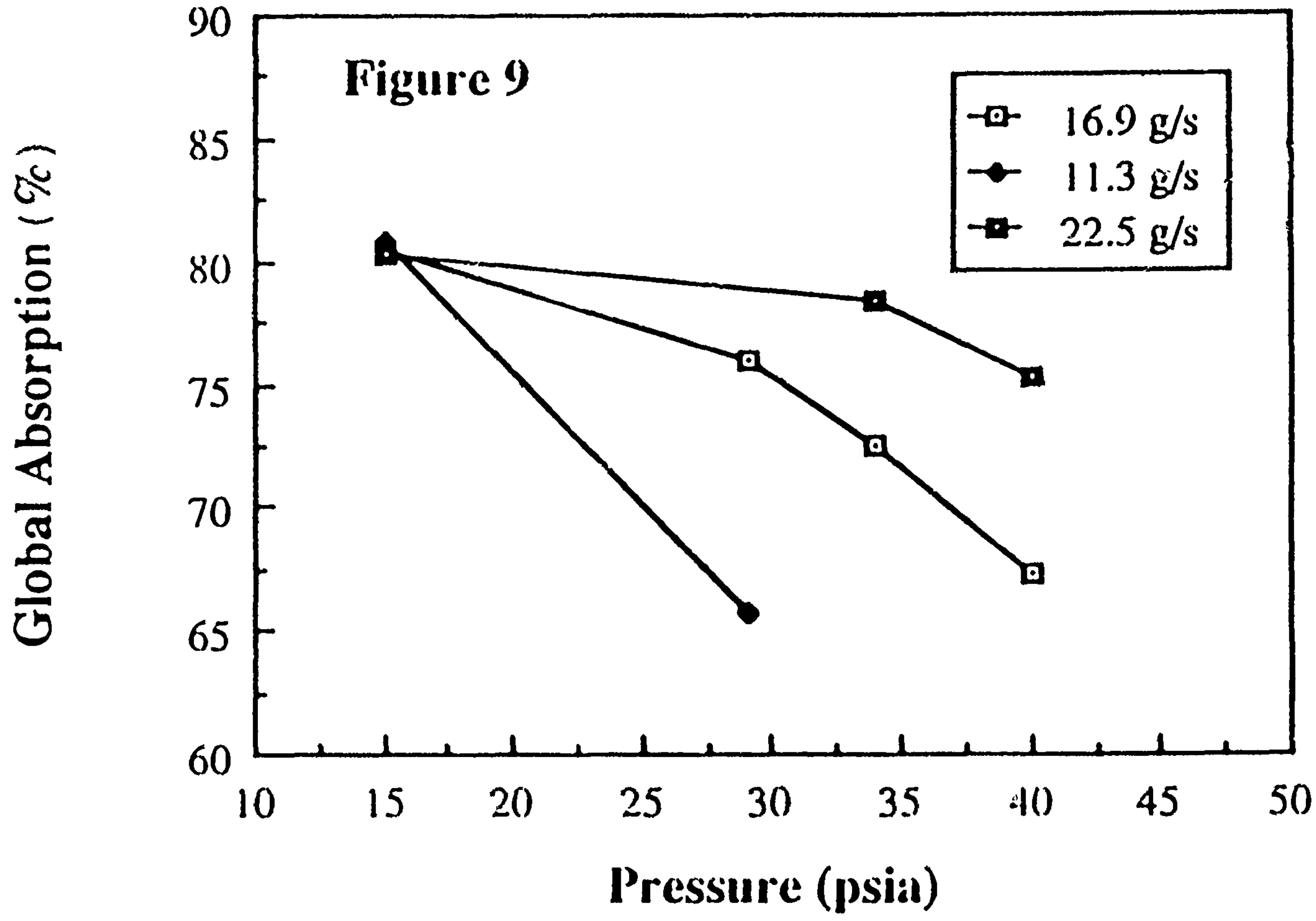




Plasma Absorption at 16.9 (g/s) and Various Pressures
Global Absorption (%)
90
85
80
75
70
65
60
0
1
2
3
4
5
6
7
8
Power (kW)
15 psia
29 psia
40 psia
35 psia
Figue 8

Figure 8

Plasma Absorption at 4 kW and Various Mass Flows



LASERS AVAILABLE FOR LASER PROPULSION:
SOLAR-PUMPED LASER OPTION

by

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Presented at AFOSR Laser Propulsion Workshop

University of Illinois

February 8-10, 1988

High-Power Lasers for Laser Propulsion: Solar Pumped Laser Option

I. Introduction

Laser propulsion systems utilize the energy of a high power laser beam to heat a propellant for production of thrust from the propellant expansion. Recently much progress has been made in the development of high-power lasers, especially free electron lasers (FELs), which could be scaled-up to the power level required for propulsion. The laser propulsion systems are divided into three types, namely, continuous-wave (CW), repetitively pulsed (RP) and advanced or hybrid propulsion systems. Therefore, the requirements for lasers vary accordingly. However, the average powers delivered by the lasers are estimated to be 10-MW level for orbit-to-orbit maneuvering and 1-GW level for earth-to-orbit launching of useful payloads. It is obvious that even the highest laser power ever developed to date is still a few orders of magnitude below that required for propulsion. Therefore, the choice of the lasers to be developed for laser propulsion must first be based on their power scalability. Beam transmission characteristics for long distances are also basic criteria for the choice.

II. Ground-Based Lasers

The concept of ground-based lasers with relay mirrors in space for laser propulsion is an emerging new approach to advance launching of spacecraft. The lasers capable of providing sufficient thrust to useful payloads and various mechanisms for thrust generation have already been discussed.

Figure 1 shows the state-of-the-art performance of high power lasers considered for this approach and that they are a few orders of magnitude below the requirement. However, the scaling to the power levels required seem to have no fundamental limitations and even multiple-unit laser arrays may be formed to satisfy the need. The laser propulsion systems powered by ground-based lasers have been the major approach of the AFOSR program and discussed fully at the 1986 workshop held at LLNL.[1] This talk will present other options with space borne light weight systems.

III. Space Borne Lasers for Propulsion

Although ground-based lasers could be developed for earth-to-orbit launching, space-borne laser systems provide many advantages not only for orbit maneuvering[2] but also for earth-to-orbit launching. The most troublesome aspect of the ground-based laser system for propulsion is earth atmospheric intervention of laser power transmission between the laser and the space relay mirror. Having the space borne laser system, all-weather launching could be made when chemical propulsion is used for the first stage to lift the payload above the tropopause. On the other hand the space borne laser systems require costly launching of the laser system and subsequent refueling of the active materials. Therefore, the evaluation of these systems should be made with respect to the masses of the system and fuel. The candidate space borne lasers are classified in figure 2.

a. Electric Discharge Lasers: Figures 3 and 4 compare one-megawatt lasers driven by the solar-photovoltaic power generated in space.[3] Figure 3 lists the intrinsic, electric, and overall efficiencies and the areas of the

solar photovoltaic panels and the radiators for cooling the laser systems. The diode laser array is included in the table since its recent development achieved high power output (1 watt per cell) and it should be possible to fabricate laser arrays with a large number of cells. Figure 4 shows the comparison of the system masses of these lasers. The masses estimated here are based on the recent references as cited.

It is obvious that the diode array is the lightest of four systems compared. This result is due to the high efficiency (30 percent intrinsic, 5 percent solar-to-laser) and to the minimal electric power conditioning required for its low voltage operation. However the large scale diode array has not been considered for laser power transmission and technology issues arise about the attainment of a beam quality needed for long distance transmission of the beam. Further discussion will be made later.

b. Direct and Indirect Solar-Pumped Lasers. Under this category we include the iodine, IBr, solid-state Nd^{3+} in host crystals, CO_2 and CO lasers excited by solar energy without converting it to electrical power. Figure 5 is a summary of the direct solar-pumped iodine laser research[4-6] pursued at NASA Langley Research Center. There are other high-risk solar-pumped laser systems as listed in figure 2. However, these are not developed to the power level that should be considered here. The results of a 1-megawatt iodine laser system study[7] are shown in figure 6. Note that a large portion of the total mass is due to the common subsystems required for all types of the system. The major items are the laser transmission optics and the attitude control system. To compare fairly the mass of the diode array which was cited earlier but did not include these subsystems, the sum (30,270 kg) of the masses for the solar collector (14,800 kg) and the radiator (15,470 kg) (no

power conditioning) from the table should be used. We see that the iodine laser and diode array systems have closely comparable masses (30,000/45,000 kg). The beam profile control issue that is of concern for the large diode array system can be easily resolved for the iodine system by adapting a master oscillator power amplifier (MOPA) scheme, in which the beam profile is easily controlled by a small master oscillator. If the beam profile control of the diode array is not solved the diode array may be forced to pump other laser systems such as Nd^{3+} solid state lasers. When such methods are adopted, the system mass increases to 99,576 kg for 1 MW output and is no longer justified for the space borne laser system. The mass increase is due mainly to a low overall efficiency (2.1 percent) of the solid state laser pumped by the diode array. Figure 7 gives the details of this estimate. One notices that the overall efficiency is reduced by a factor of three for adopting the diode pumped solid state system and accordingly the system mass increases significantly.

Figure 8 is a schematic representation of the solar-pumped laser power station.[5] The solar rays are collected by the pseudo-parabolic solar collector and directed toward the laser tube placed along the axis. The laser medium in the gas phase absorbs the near UV band and transmits all other remaining wavelengths to space. Therefore, the transmitted energy does not become the thermal load to the system. This fact is very important to consider for determining the cooling requirement. The solar collector can be fabricated with a thin aluminum coated film with 0.1 kg/m^2 density. For 1 MW output, the laser medium must absorb approximately 5 MW for the intrinsic efficiency of 21 percent. Since the energy in the near UV band effective for t-C_4F_9I in the air mass zero solar irradiance spectrum is only 3 percent, the total solar energy of 162 MW must be collected, although most of it (157 MW)

is uneffective and returns to space. This calls for a large solar collector (122,665 m^2, 395.3 m diam.). Figure 9 depicts the thermal and flow cycle calculations. Notice that the radiator is required for only 4 MW of cooling power. For details of these calculations see the reference 7. The study presents a conclusion that the solar-pumped 1-megawatt iodine laser system with a mass of 92,000 kg can be adopted for the laser power station in a medium high orbit 6378 km. The mass of the system corresponds to the payload capability of four space shuttle flights. Since there seems to be no fundamental limit for scaling this system, the requirements of laser propulsion could be met by future development of this system.

IV. Conclusion

The candidate lasers suitable for laser propulsion have been discussed for their adoption to the ground-based and space borne systems. The recently developed high-power diode laser array is included for evaluating the laser power transmitters. It is found that the diode laser array could be a light-weight system suitable for using on the space borne power station, as is the direct solar-pumped iodine laser system under study at NASA. However, beam profile control is required for the diode laser array and a breakthrough in this field is necessary. The direct 1-megawatt solar-pumped iodine laser system corresponds to only four shuttle payloads for its unique system kinetics and no fundamental limit to inhibit further scaling of this system is likely to exist.

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LASERS AVAILABLE FOR LASER PROPULSION:

SOLAR-PUMPED LASER OPTION

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AFOSR LASER PROPULSION WORKSHOP
URBANA-CHAMPAIGN, IL.
FEB 8-10, 1988

LASERS AVAILABLE FOR LASER PROPULSION

- REQUIREMENTS (FROM 1986 WORKSHOP):

LASER POWER	> 10 MW	ORBITAL MANEUVERING
	> 1 GW	EARTH-TO-ORBIT LAUNCHING (> 1 TON)
PHOTON FLUX	$< 2 \times 10^5$ W/cm^2	CW
	$< 2 \times 10^7$ W/cm^2	PULSED (LSD PROP.)
WAVELENGTH	> 10 μm	INVERSE BREMSSTRAHLUNG - H_2 (1 μm IF BEAM TRANSPORT THROUGH ATMOSPHERE SOLVED.)
PULSE WIDTH	50 ns - 1 μs	PLASMA GEN. AND HEATING
EFFICIENCY	HIGH	

- GROUND BASED WITH SPACE RELAY

  FREE ELECTRON LASER, CO_2 LASER

  STATE-OF-THE-ARTS: MULTI-KILOWATT (CW), 500 kJ (PULSED)

  SCALING-UP: POSSIBLE TO MULTI-MW LEVEL.

- TECHNICAL ISSUES:

  MANY ORDERS OF MAGNITUDE UP-SCALING NEEDED

  ATMOSPHERIC INTERFERENCE

  SPACEBORNE LASER OPTION SHOULD BE CONSIDERED

Figure 1

SPACE-BORNE LASERS FOR PROPULSION

O SOLAR POWERED LASERS

DIRECT SOLAR PUMPED LASERS

IODINE PHOTODISSOCIATION LASER, IBR PHOTODISSOCIATION LASER

SOLID STATE LASERS (ND^{3+}), LIQUID ND^{3+} LASERS, DYE LASERS

INDIRECT SOLAR PUMPED LASERS

N_2-CO_2 BLACKBODY PUMPED LASER, CO BLACKBODY PUMPED LASER

SOLAR PHOTOVOLTAIC POWERED

ELECTRIC DISCHARGE LASERS (EXCIMER, COPPER, CO_2, DIODE)

FEL (TOO HEAVY FOR LAUNCHING)

O NUCLEAR POWERED LASERS

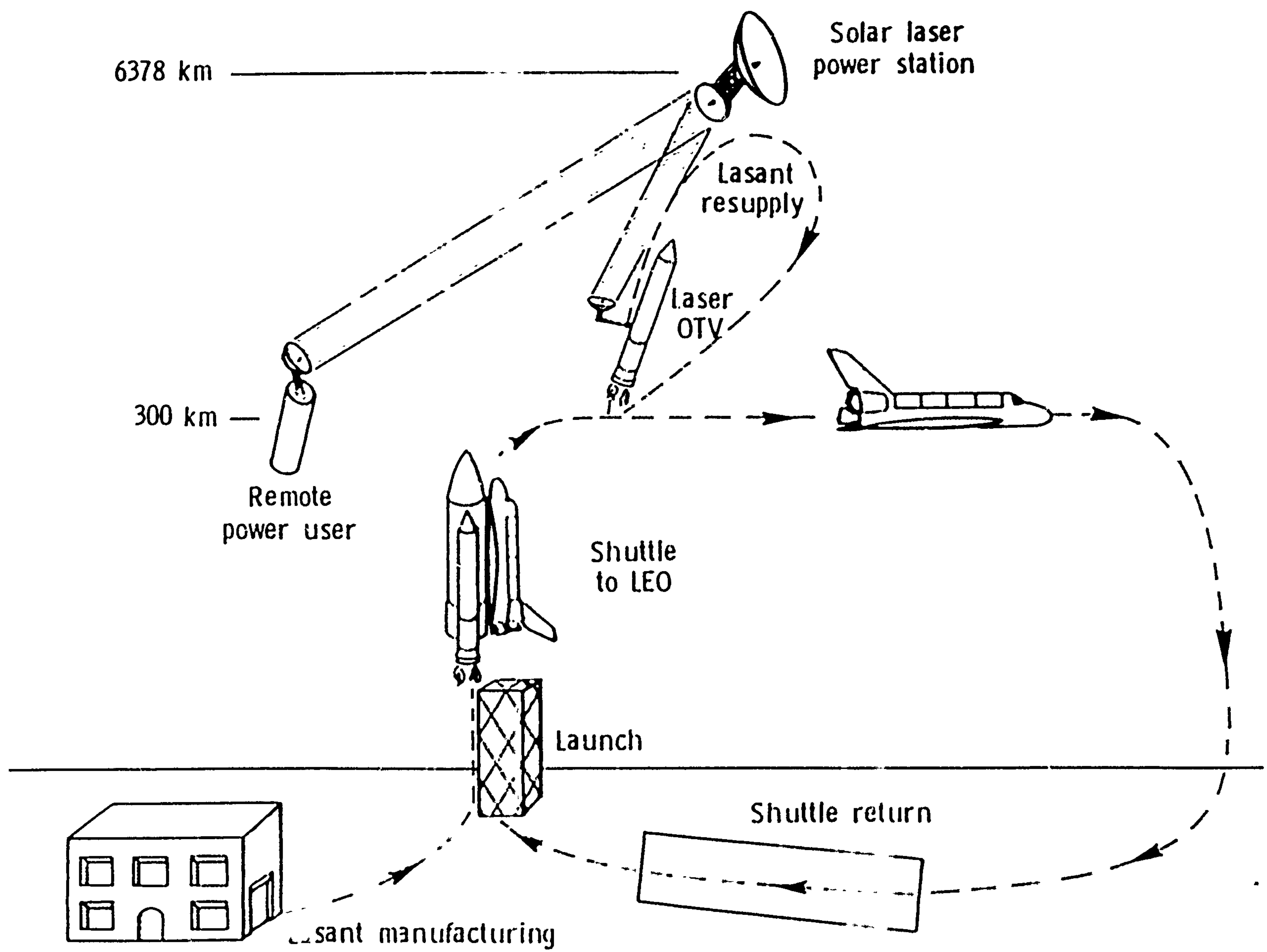
DIRECT NUCLEAR-PUMPED LASERS

HIGH EFFICIENCY ELECTRIC DISCHARGE LASERS

(MAY BE IMPRACTICAL FOR HEAVY SYSTEM WEIGHT)

Figure 2

OPERATION OF SOLAR PUMPED LASER POWER STATION



SOLAR PHOTOVOLTAIC ELECTRICALLY PUMPED ONE MW LASER SYSTEMS

		KrF EXCIMER	COPPER VAPOR	DIODE ARRAY	CO_2	REMARKS
LASER WAVELENGTH	μM	0.248	0.510 0.570	0.8	10.6	
INTRINSIC EFFICIENCY	%	10	5	30	13.7	
ELECTRIC EFFICIENCY	%	2.5	1.4	30	5.5	WALL-PLUG EFF.
SOLAR TO LASER EFFICIENCY	%	0.40	0.24	6.0	0.88	
SOLAR POWER COLLECTED	MW	250	412	16.5	113.5	
ELECTRIC POWER FROM PV ARRAY	MW_E	50	82	3.3	22.7	20 PERCENT EFFICIENCY
SOLAR PANEL AREA	M^2	185,185	305,185	12,318	84,444	$1.35 KW/M^2$ AMO
THERMAL RADIATED POWER	MW	40	81	2.3	21.7	OTHER THAN SOLAR ARRAY
RADIATOR TEMP./AREA	$K/1000M^2$	300/21.8 373/27.3 326/14.1	300/107 1770/.057	250/10.4 - - -	300/9.8 409/10.8	
	TOTAL	63.2	107.057	10.4	20.6	

Figure 3

SOLAR PHOTOVOLTAIC PUMPED ONE MW LASER SYSTEMS

		KrF EXCIMER	COPPER VAPOR	DIODE ARRAY	CO_2	REMARKS
ELECTRIC EFFICIENCY	%	2.5	1.4	30	5.5	AFTER POWER CONDITIONING
ELECTRIC POWER	MWE	50	82	3.3	22.7	
SOLAR PANEL AREA,	M^2	185,185	305,185	12,318	84,444	20% EFFICIENCY
MASS	KG	166,666	273,333	11,000	76,000	300 W/KG (REF. 1)
POWER CONDITIONER	KG	88,000	144,320	5,808	40,120	1.76 KG/KWE (REF. 2)
THERMAL POWER	MW	49	81	2.3	21.7	
RADIATED						
RADIATOR AREA	M^2	63,200	107,057	10,400	20,600	
MASS	KG	170,640	289,054	28,080	55,620	2.7 KG/M^2 (REF. 3)
TOTAL MASS	KG	425,306	706,707	44,888	171,740	LASER CAVITY MASS NOT INCLUDED

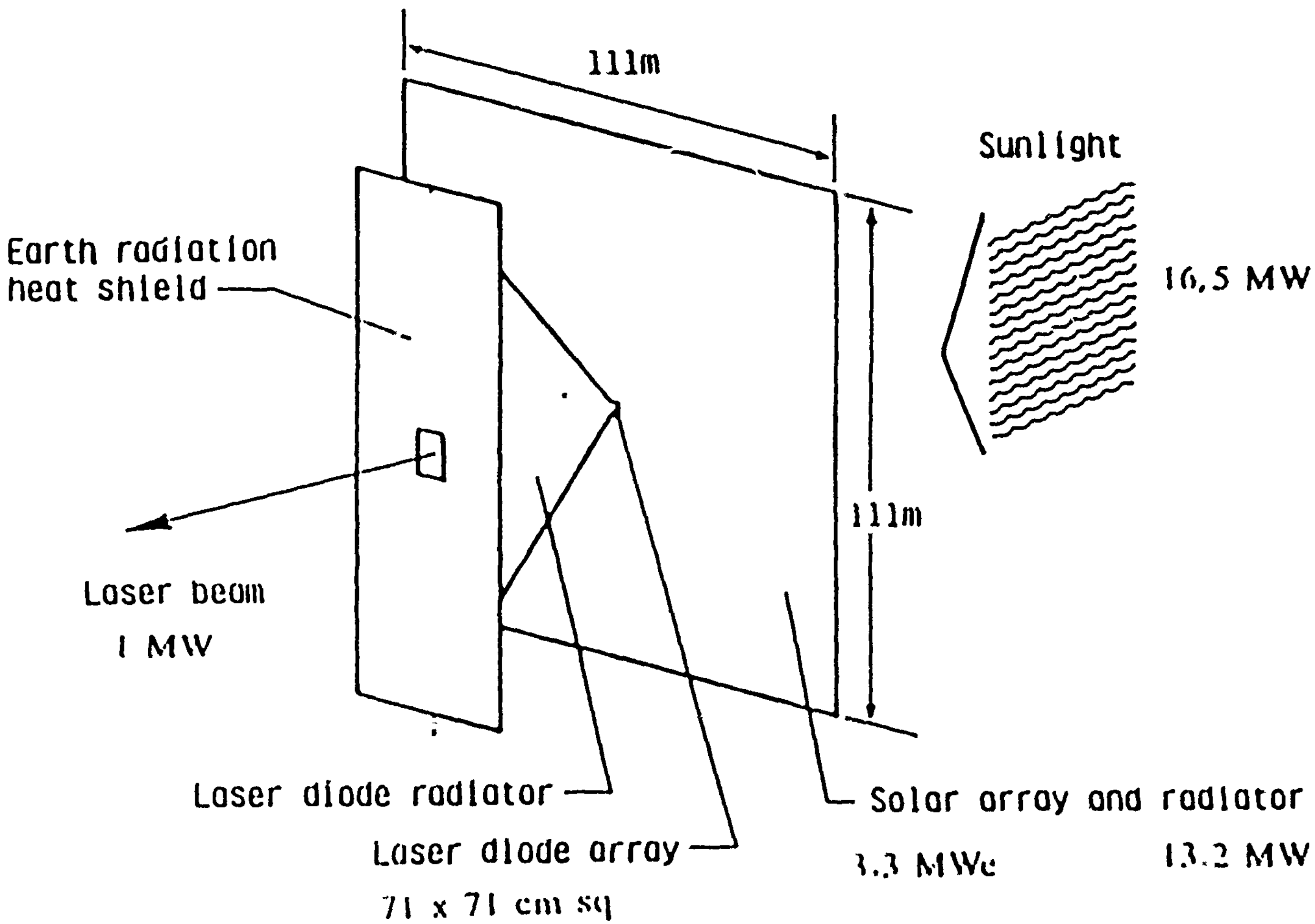
REF. 1 - E. A. GABRIS AND A. D. SCHNYER, PROC. 22ND IECEC AUG 1987, P. 33

2 - J. A. MARTIN AND L. WEBB, PROC. 22ND IECEC AUG 1987, P. 321

3 - E. P. FRENCH, 15TH IECEC, 1980, P. 394.

Figure 4

1MW LASER DIODE ARRAY SYSTEM



LASER DIODE ARRAY TECHNICAL ISSUES

ADVANTAGES:

- 0 HIGH SYSTEM EFFICIENCY (6%)
- 0 SMALL AND POTENTIALLY LEAST MASSIVE SYSTEM
- 0 NO LASANT FLOW REQUIRED
- 0 REASONABLE LASER WAVELENGTH
- 0 LASER DIODE ARRAY HAS GOOD POWER COUPLING TO SOLAR ARRAY
- 0 LOW WEIGHT/SIZE WASTE HEAT RADIATOR

DISADVANTAGES:

- 0 LOW TEMPERATURE LASER OPERATION REQUIRES LOW T RADIATOR AND HEAT REMOVAL SUBSYSTEM
- 0 VERY TEMPERATURE SENSITIVE
- 0 EFFECTS OF SPACE RADIATION MAY BE SEVERE

TECHNICAL ISSUES:

- 0 PHASE MATCHING ENTIRE LASER ARRAY NOT DEMONSTRATED
- 0 SCALING PRESENT 1-WATT SINGLE DIODES TO 1MW DIODE ARRAY
- 0 ARRAY COOLING WITH HEAT PIPES
- 0 ELECTRICAL DIODE LASER NETWORK

STATUS OF SOLAR-PUMPED IODINE LASER

O KINETICS:	LASER MEDIUM	C_3F_7I, C_4F_9I
	99 PERCENT RECYCLABLE	
	PUMP BAND	250-290 nm NUV
	INTRINSIC EFFICIENCY	21 PERCENT
	EXCITATION MODE	PHOTODISSOCIATION TO I*
	SOLAR-TO-LASER EFFICIENCY	0.2 TO 0.6 PERCENT

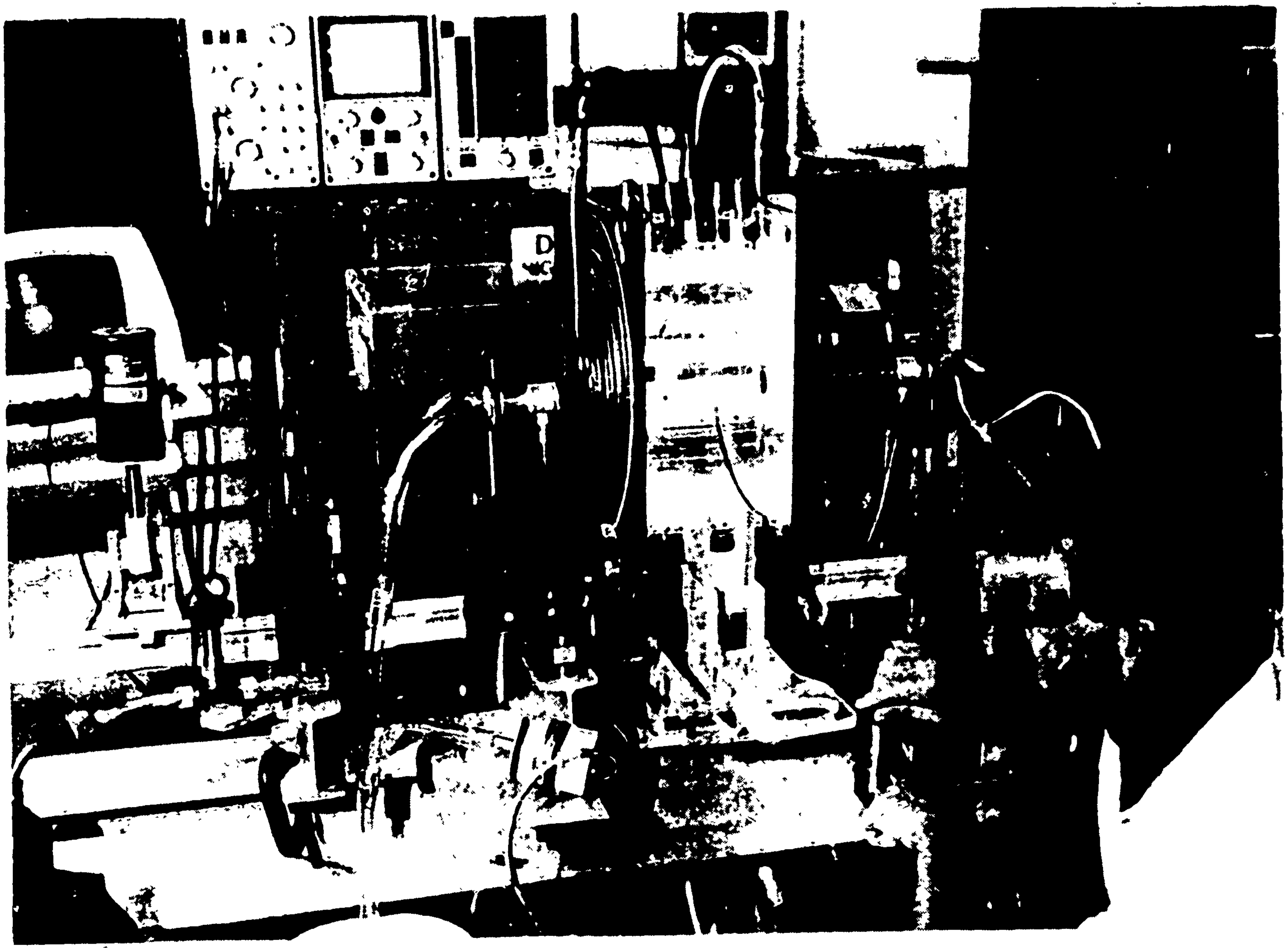
O SCALABILITY:
- PULSED POWER > 2 TW/2 KJ ACHIEVED (MARX PLANCK INT.)
- CW > 15 W ACHIEVED (WITH SOLAR SIMULATOR)
- SCALING NO THEORETICAL LIMIT, 1 GW LEVEL POSSIBLE
- 1MW SYSTEM STUDY COMPLETED

O SOLAR-SIMULATOR PUMPED LASER EXPERIMENT:
- 15 W CW, > 250 W PULSED (Q-SWITCHED)
- FLOW, SUBSONIC
- REP. PULSED MOPA UNDER DEVELOPMENT

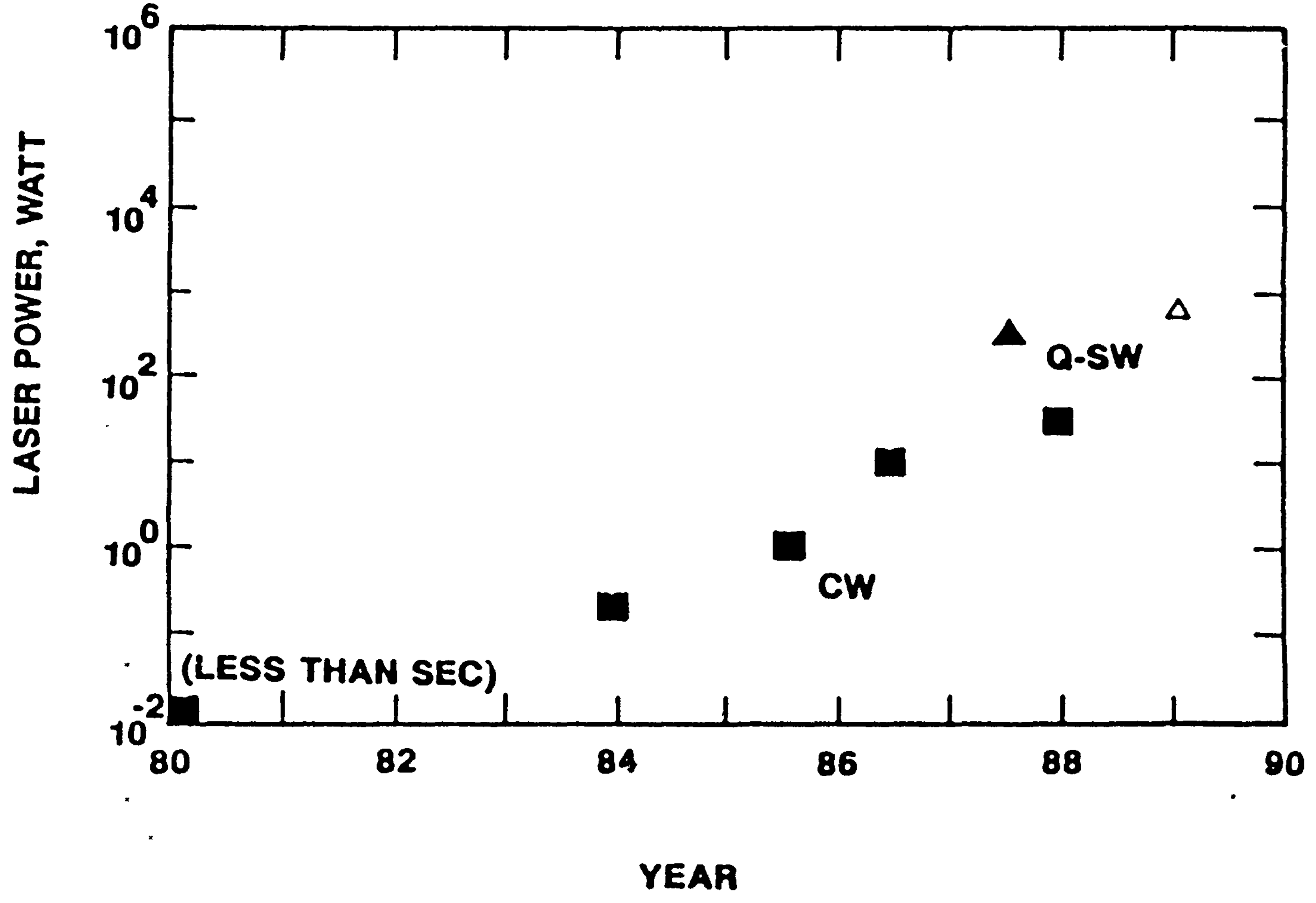
O R & D ISSUES:
- LARGE SOLAR UV COLLECTOR
- CHEMICAL REVERSIBILITY
- BEAM PROFILE CONTROL
- FLIGHT EXPERIMENT FOR THERMAL MANAGEMENT/BEAM TRANSMISSION

Figure 5

SOLAR SIMULATOR PUMPED IODINE LASER EXPERIMENT



PROGRESS IN SOLAR LASER POWER



ONE MW SOLAR IODINE LASER SYSTEM MASS

COLLECTOR, KG	14,800
RADIATOR, KG	15,470
TOTAL MASS FOR COLLECTOR AND RADIATOR, KG	30,270
OTHER SUBSYSTEMS:	
LASER CAVITY	
QUARTZ TUBE, KG	1,860
LASER CAVITY OPTICS, KG	1,000
LASER TRANSMISSION OPTICS AND STRUCTURE (27.6 M DIAM.), KG	24,000
GAS FLOW SYSTEM	
COMPRESSOR (2 STAGE), KG	12,700
TURBINE, KG	12,200
DUCTS, KG	3,000
T-C_4F_9I STORAGE TANKS (4 EMPTY TANKS), KG	270
ATTITUDE CONTROL SYSTEM (CMG AND FUEL)	
CMG, KG	2,000
150 KG FUEL/YR, KG	4,500

Figure 6

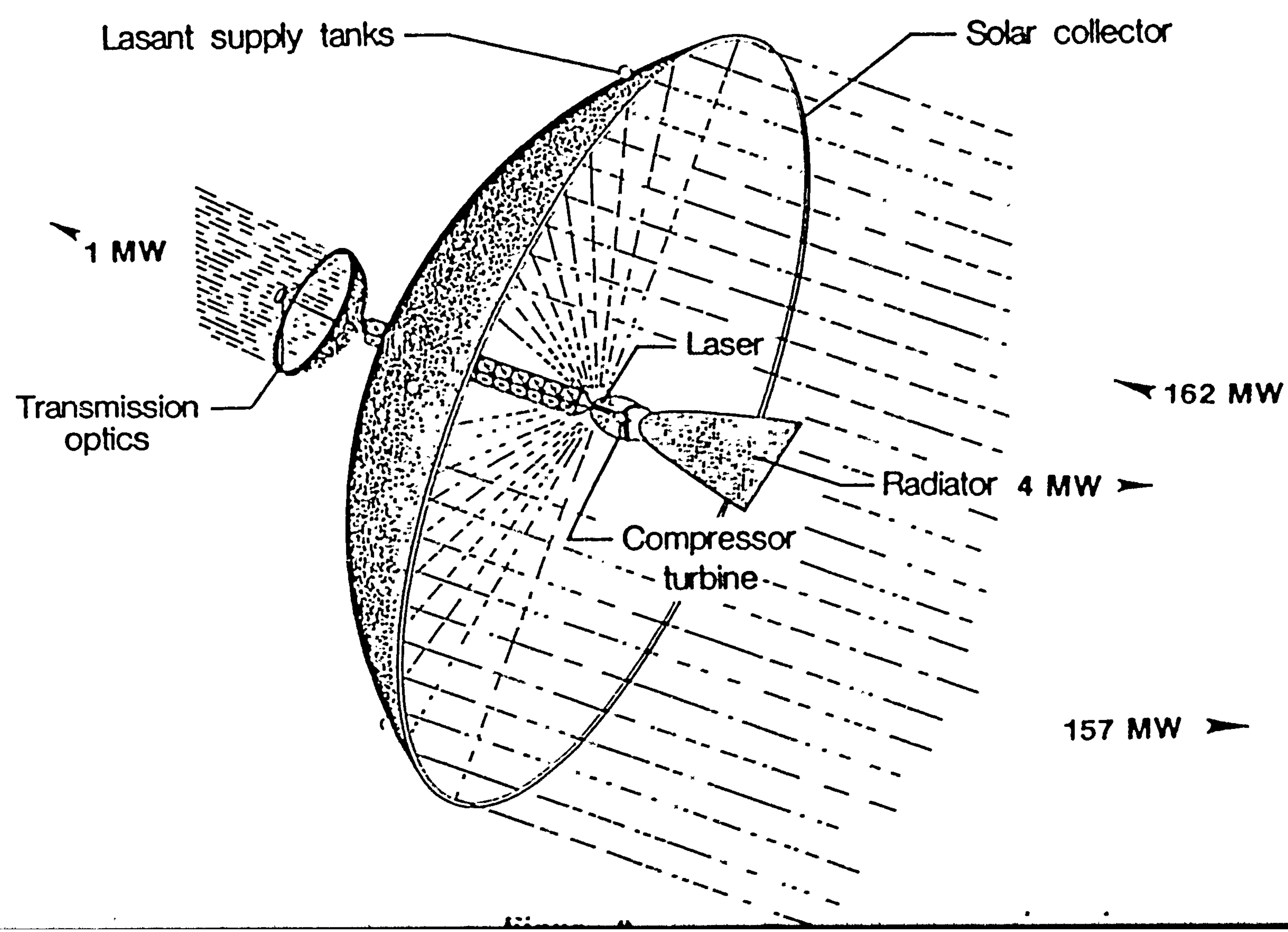
WEIGHT ESTIMATE OF DIODE PUMPED Nd YAG LASER SYSTEM

DIODE LASER EFFICIENCY		= 30%	
PUMPING EFFICIENCY		= ND:YAG LASER OUTPUT/DIODE LASER INPUT	
		= 35%	(REF.)
ELECTRIC EFFICIENCY		= 10.5%	
SOLAR DIODE LASER EFFICIENCY		= 6%	
OVERALL SYSTEM EFFICIENCY		= .06 X .35 = .021 OR 2.1%	
SOLAR POWER COLLECTED		= 1-MW/.021 = 48 MW	
ELECTRIC POWER		= 48 MW X .20 = 9.6 MWE	
		6.72 (THERMAL) + 2.88 MW (LASER)	
SOLAR PANEL	AREA	35,477 M^2	
	WEIGHT	32,000 KG	300 WR/RG
POWER CONDITIONING		16,896 KG	1.76 KG/KWE
COOLING POWER		8.6 MW	
RADIATOR TEMPERATURE		300 K/350 K	
	AREA	18,770 M^2	
	WEIGHT	50,680 KG	2.7 KG/M^2
TOTAL WEIGHT		99,576 KG	

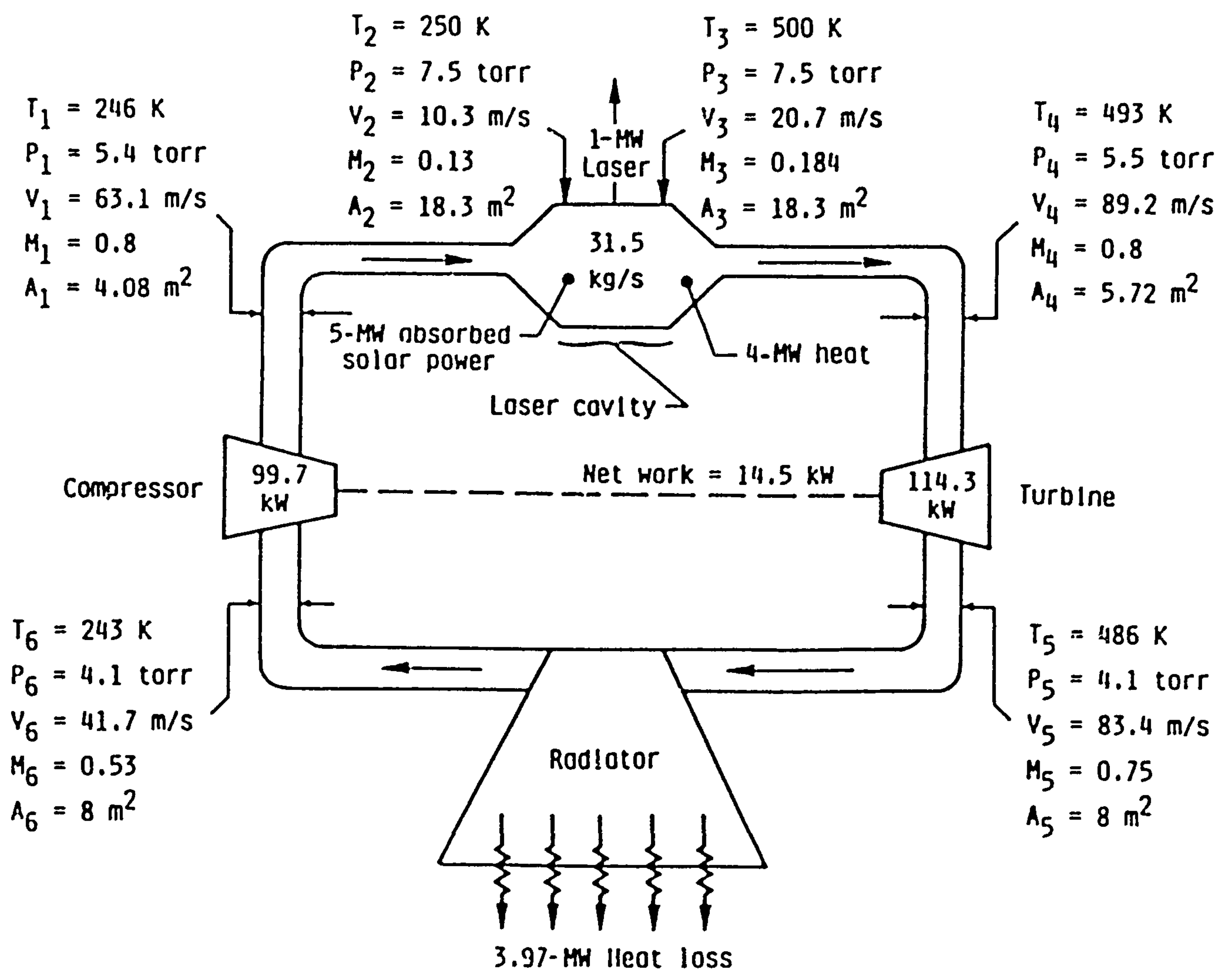
COMPARE: 44,888 KG FOR DIODE LASER ARRAY AND
30,270 KG FOR SOLAR IODINE LASER

Figure 7

ONE MEGAWATT IODINE SOLAR PUMPED LASER POWER STATION

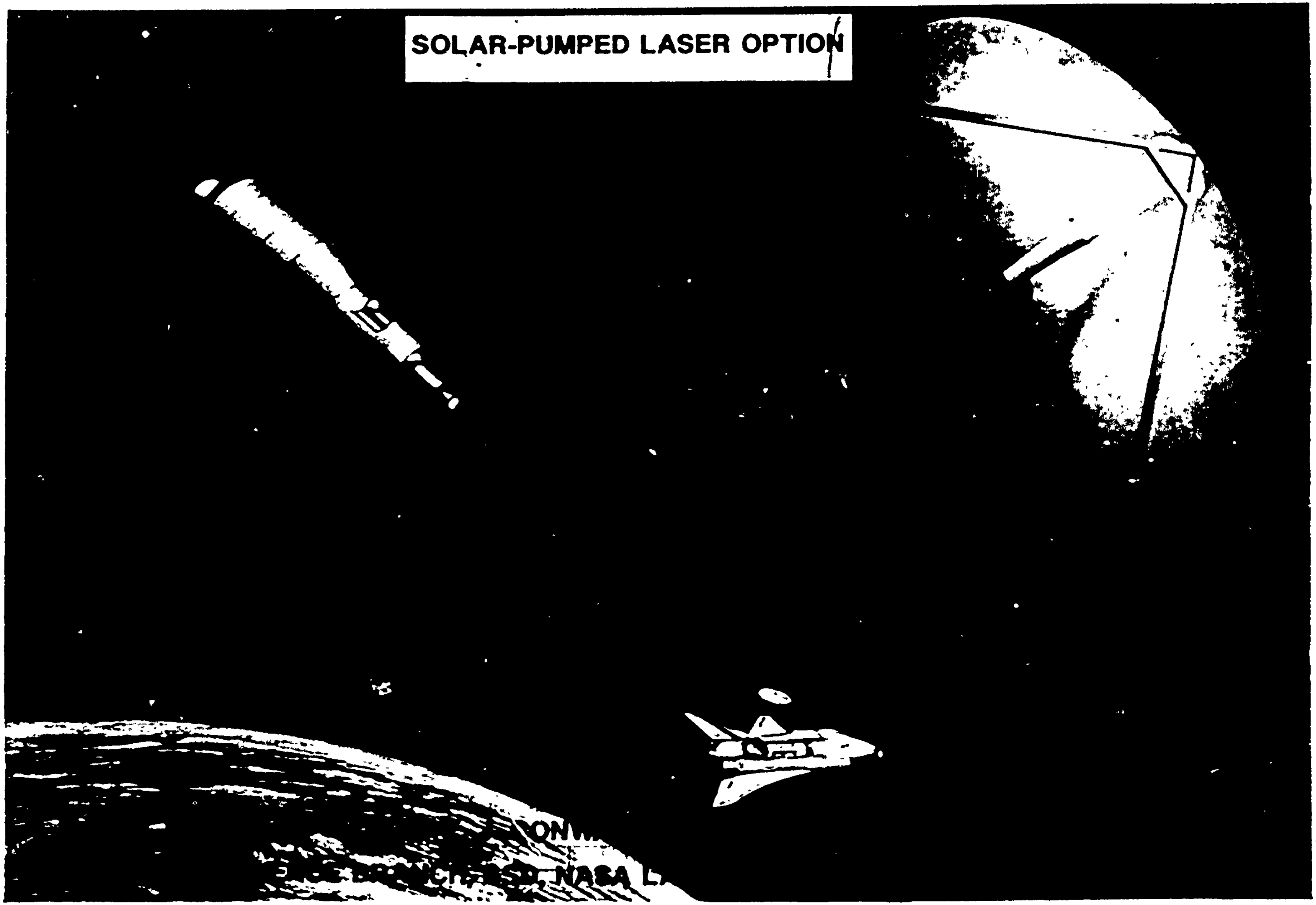


FLOW AND THERMAL CYCLES OF ONE MW IODINE LASER



169/170

LASERS AVAILABLE FOR LASER PROPULSION:



SUNMMARY AND CONCLUSIONS

- O SPACE-BORNE SOLAR-PUMPED LASER SYSTEMS ARE VIABLE OPTIONS FOR LASERS FOR LASER PROPULSION. FREE POWER SOURCE, SUN, IS USED AND THE SYSTEM IS FREE FROM ATMOSPHERIC INTERFERENCE.

- O SOLAR-PUMPED IODINE LASER SYSTEM HAS SCALABILITY AND LIGHT WEIGHT (30 TONS/1 MW) SUITABLE FOR SPACE-BASED OPERATION.

- O DOIDE LASER ARRAYS DRIVEN BY SOLAR PANELS COULD BE ANOTHER CANDIDATE FOR THE SPACE-BASED LASER SYSTEM IF BEAM PROFILE CONTROL FOR THE LONG DISTANCE TRANSMISSION IS POSSIBLE.

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7. De Young, R. J.; Walker, H. G.; Williams, M. D.; Schuster, G. L.; and Conway, E. J.: Preliminary Design and Cost of a 1-Megawatt Solar-Pumped Iodine Laser Space-to-Space Transmission Station, NASA RM-4002. Sept 1987.

COMPUTATIONAL SOLUTION OF LOW SPEED FLOWS WITH STRONG ENERGY ADDITION

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University Park, PA 16802

The highly developed numerical algorithms from external aerodynamics are being used to calculate low speed flows with strong energy addition, including laser supported plasmas. These algorithms are well understood mathematically, are of high accuracy with low numerical dissipation and are easily expressed in arbitrary bodyfitted coordinates so they can be routinely used on realistic geometries. In addition, they apply to viscous or inviscid problems, an attribute that is extremely important for high Reynolds number flow calculations, and they can be used for steady or unsteady flows. The use of a time-like procedure enables both initial and boundary conditions to be formulated in a manner analogous to experiment. Unfortunately, these transonic flow techniques are inefficient at low speeds and require adaptation for the present class of problems. Appropriate adaptations for low speeds and low Reynolds number conditions have been developed and are given below along with applications to laser-supported plasma calculations.

There are two basic procedures that can be used to ensure convergence of a numerical scheme in a particular problem. In the one, the iterative technique is modified to give a convergent solution to the desired flowfield. In the second, the flowfield itself is changed (by adding numerical viscosity) until convergence can be attained. The former method has been used here, starting with the inviscid and then proceeding to the viscous problem.

In inviscid flows, the convergence rate slows down rapidly as the Mach number is decreased because of the interaction between the stiff eigenvalues and the approximate factorization used in implicit schemes (Figs. 1 and 2). This slowdown is easily offset by rescaling the eigenvalues (Fig. 3), but this inviscid rescaling becomes inappropriate as the Reynolds number is reduced to the low values that are representative of laser-supported plasmas (Figs. 4 and 5). The addition of a viscous scaling in combination with the inviscid eigenvalue control provides convergence that is independent of both Reynolds number and Mach number from transonic, high Reynolds number conditions to low speed, low Reynolds number conditions (Figs. 6 and 7).

Representative results obtained with this modified algorithm are shown in Figs. 8 and 9. The temperature and velocity contours in a duct with volumetric heat addition (Fig. 8) and convective heating through the walls (Fig. 9) are shown for low speed flow and Reynolds numbers ranging from infinite (inviscid) to 0.05. Essentially identical rates of convergence were observed in all cases. It is emphasized that this convergence was not done by adding dissipation to the solution, but by properly choosing the time-marching (iteration) path. The results show the expected increasing effects of diffusion as Reynolds number is decreased and the totally different character of the flowfields in these different regimes. A summary of the Mach number/Reynolds number regime over which effective convergence is obtained is also shown (Fig. 10) along with the bounds of the unmodified procedure.

With these modifications (summarized in equation form on Fig. 11), the centrally differenced algorithm can now be applied to laser-supported plasma calculations. A representative flow and radiation grid is given

on Fig. 12. The coupling of the radiation field with the flow equations does affect convergence, and several alternatives are available. A direct implicit solution of both radiation and fluids (Fig. 13) gives an extremely robust solver that provides convergence to machine accuracy in about 10 iterations and to engineering accuracy in about 4 iterations (Fig. 14), however it is expensive in terms of CPU time. Other procedures include either direct or ADI solution of the fluids equations with iterative updates of the radiation equations (also shown on Fig. 14) Laser results for all three procedures have been obtained.

Representative results for laser absorption with a simplified re-radiation expression are shown on Figs. 15-17. Figure 15 shows the relative insensitivity of the plasma location for variations in laser power at an inlet velocity of 1 cm/s. Figure 16 shows the fairly strong forward movement of the plasma as the flow speed is reduced by two orders of magnitude. Finally, Fig. 17 shows the movement of the plasma as both the flowfield and the laser diameter are scaled. Continued scaling in laser size beyond that shown appears to result in a configuration for which laser absorption does not occur.

Additional work is in progress on improved radiation loss models to enable scale-up to larger laser sizes. Representative calculations of broad-band absorption of hydrogen-alkali metal vapor mixtures (Figs. 18 and 19) have been obtained as a first step in estimating radiative energy balances of the re-radiated energy. Major issues to be addressed in laser propulsion modeling include improved modeling of radiation losses, and size scale-up to large lasers.

COMPUTATIONAL SOLUTION OF LOW SPEED FLOWS WITH STRONG ENERGY ADDITION

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Presented at

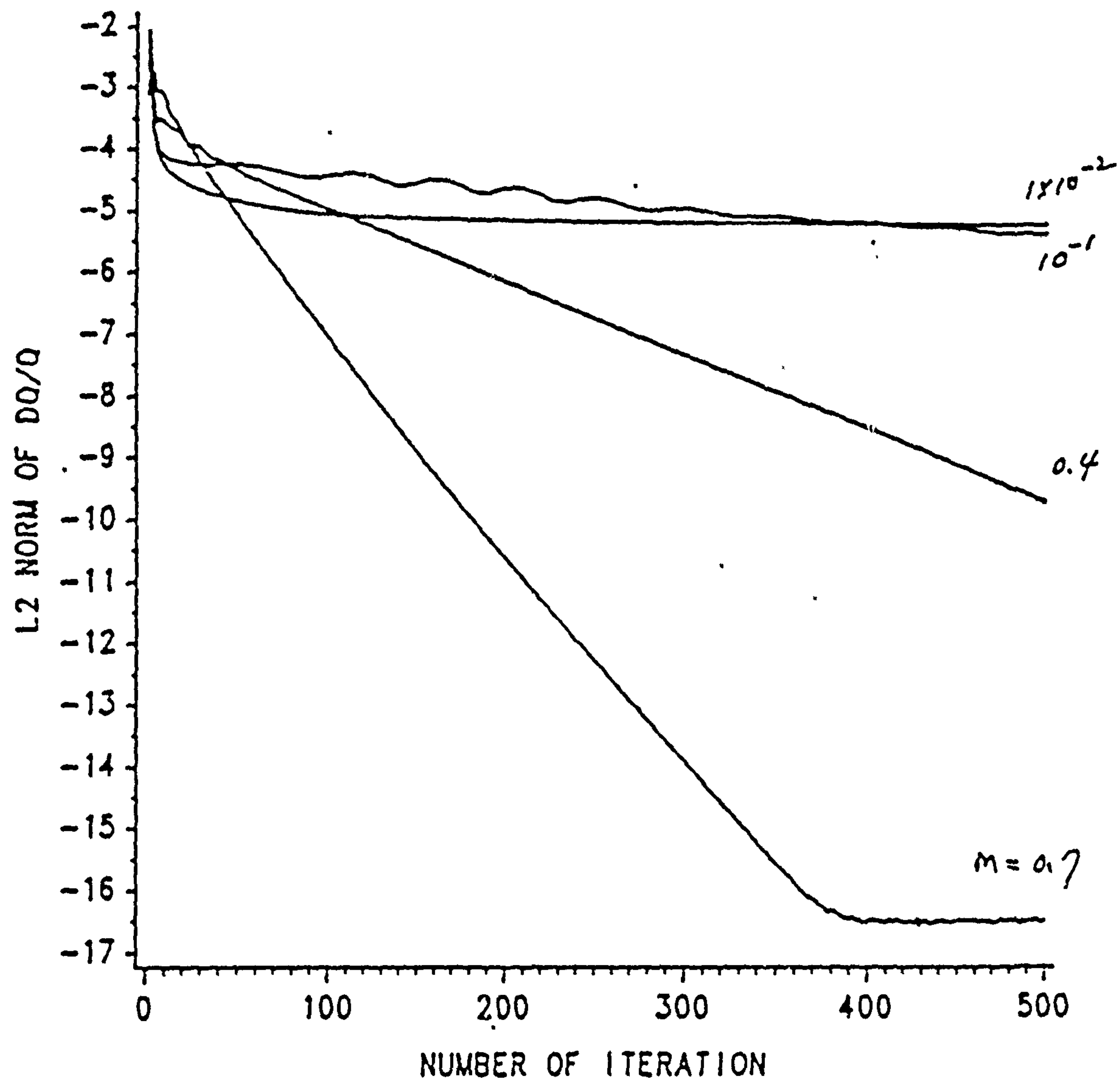
AFOSR Laser Propulsion Workshop
University of Illinois

February 8-10, 1988

CONTEMPORARY "TIME DEPENDENT" ALGORITHMS

- DEVELOPED FOR TRANSONIC AERODYNAMICS
- APPLICABLE TO:
  - Inviscid or Viscous Eqns.
  - Arbitrary Bodyfitted Coordinates
  - Steady or Unsteady Flows
- CHARACTERISTICS OF ALGORITHMS
  - High Accuracy
  - Incorporates General Iterative Procedures
  - Mathematically Well Understood
  - Low Numerical Dissipation
  - Problem Formulation Analogous to Experiment
  - Coupled or Sequential Solution
- APPLICATION TO LASER ABSORPTION
  - Low Mach Number
  - Highly Compressible
  - Coupled Radiation/Gasdynamic

Convergence for 2-dimensional compressible Euler equations



Modified Low Mach Number Viscous Formulation

$$\Gamma \partial_t Q + \partial_x E + \partial_y F = H + L(Q)$$

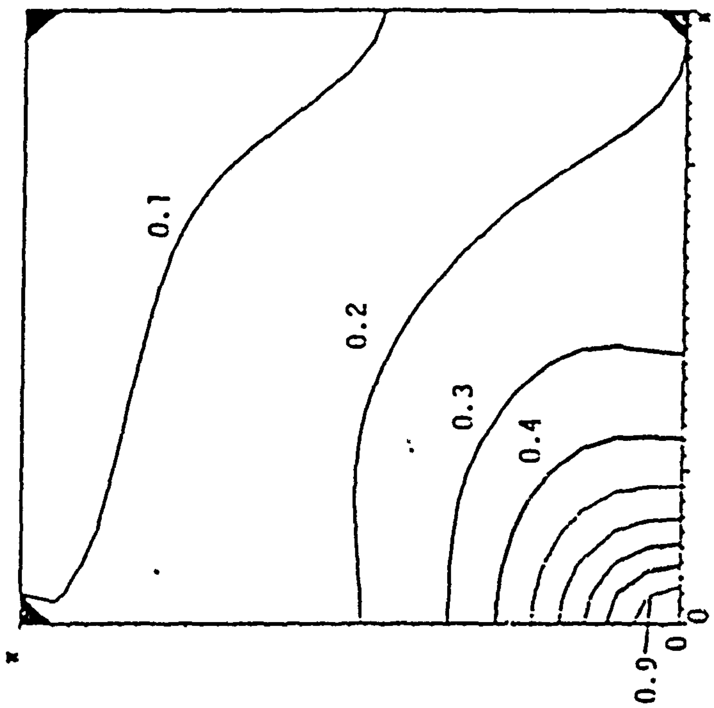
$$L = \partial_x R_{xx} \partial_x + \partial_x R_{xy} \partial_y + \partial_y R_{yx} \partial_x + \partial_y R_{yy} \partial_y$$

$$\Gamma = \begin{bmatrix} 1 & 0 & 0 & 0 \\ u & \rho & 0 & 0 \\ v & 0 & \rho & 0 \\ T & 0 & 0 & \rho \end{bmatrix}$$

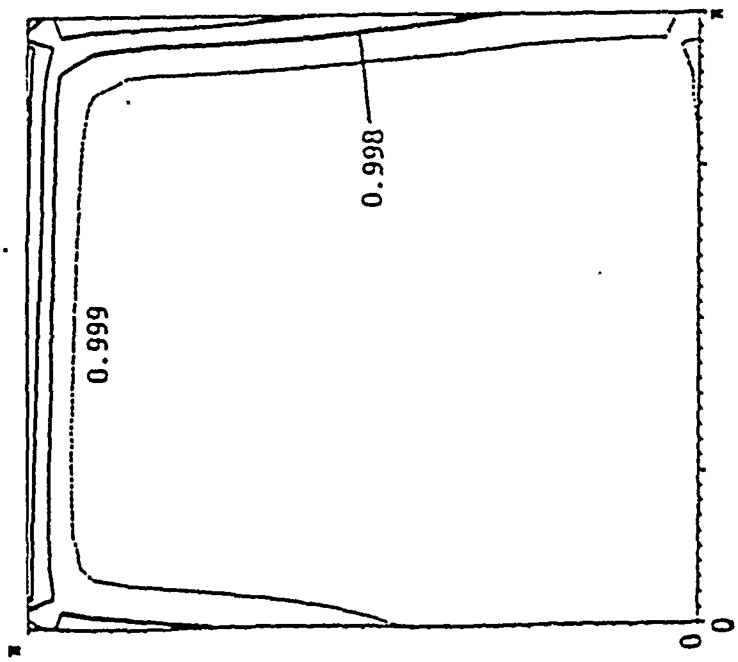
$$Q = \begin{bmatrix} p^1 \\ u \\ v \\ T \end{bmatrix} \qquad E = \begin{bmatrix} \rho u \\ \rho u^2 + p^1 \\ \rho uv \\ \rho uT \end{bmatrix}$$

$$F = \begin{bmatrix} \rho v \\ \rho uv \\ \rho v^2 + p^1 \\ \rho vT \end{bmatrix} \qquad H = \begin{bmatrix} 0 \\ -\rho/Fr \\ 0 \\ Cq/\gamma \end{bmatrix}$$

$$R_{xx} = (Re_L)^{-1} \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & (4/3)\mu & 0 & 0 \\ 0 & 0 & \mu & 0 \\ 0 & 0 & 0 & k/Pr \end{bmatrix}$$

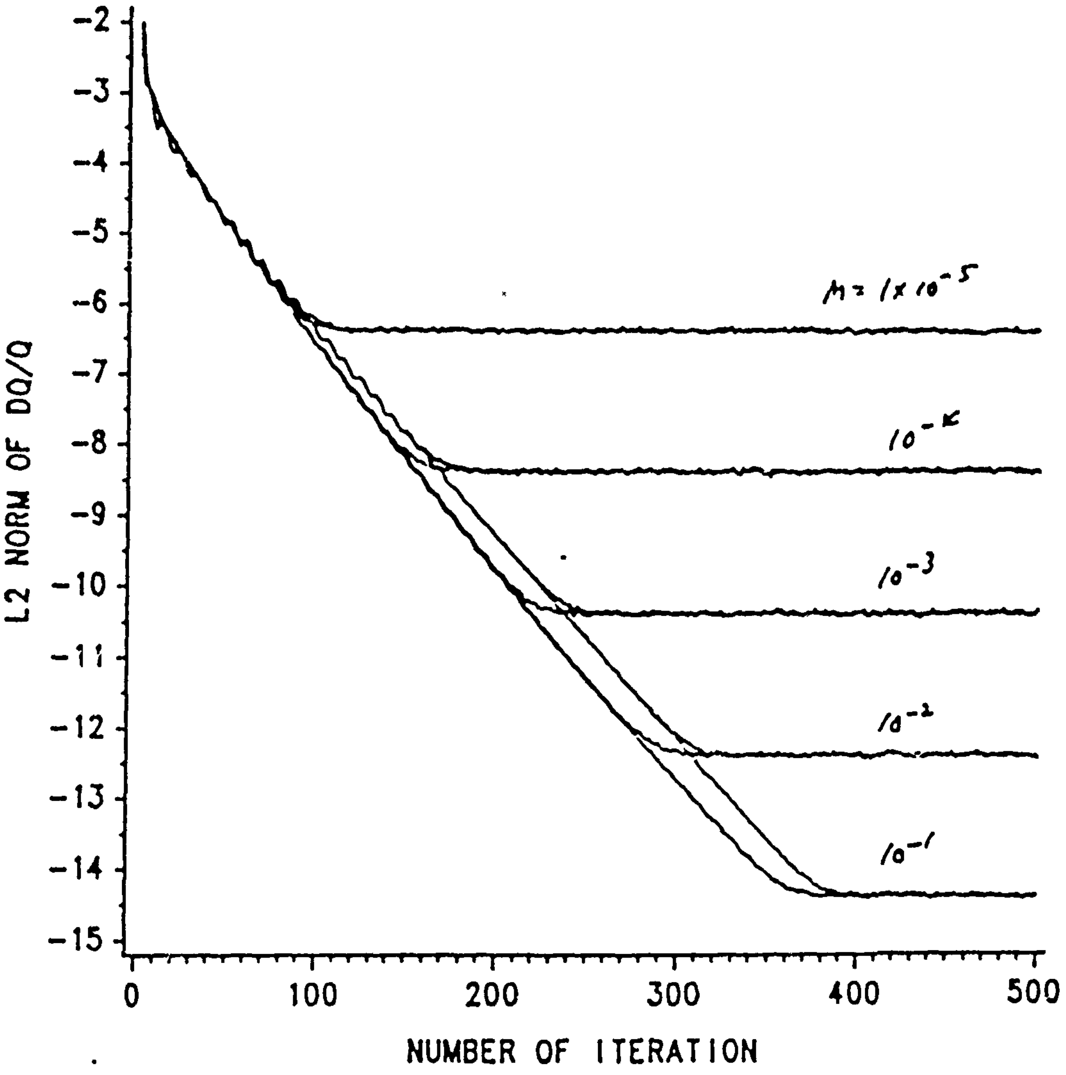


(b)



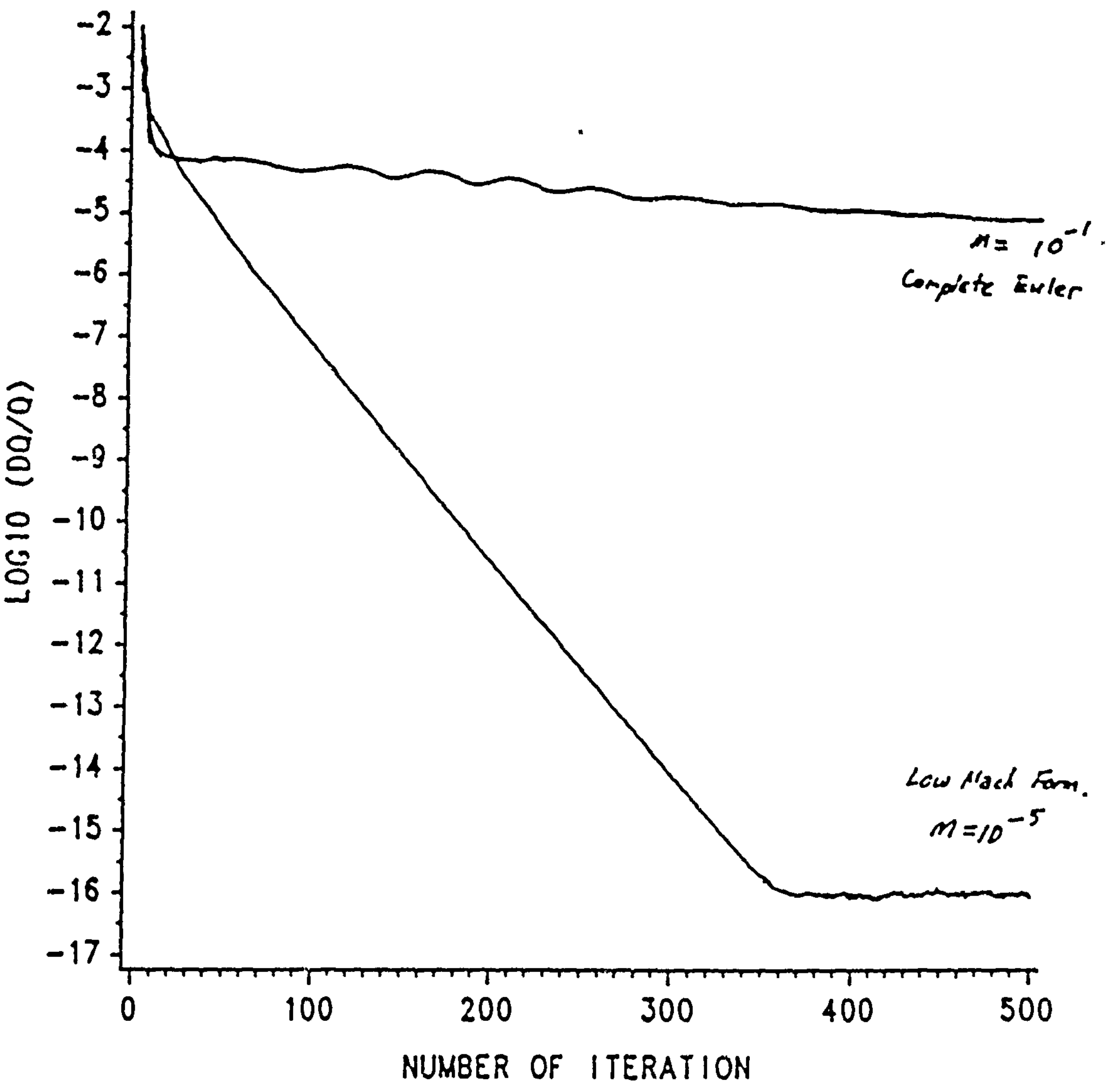
(a)

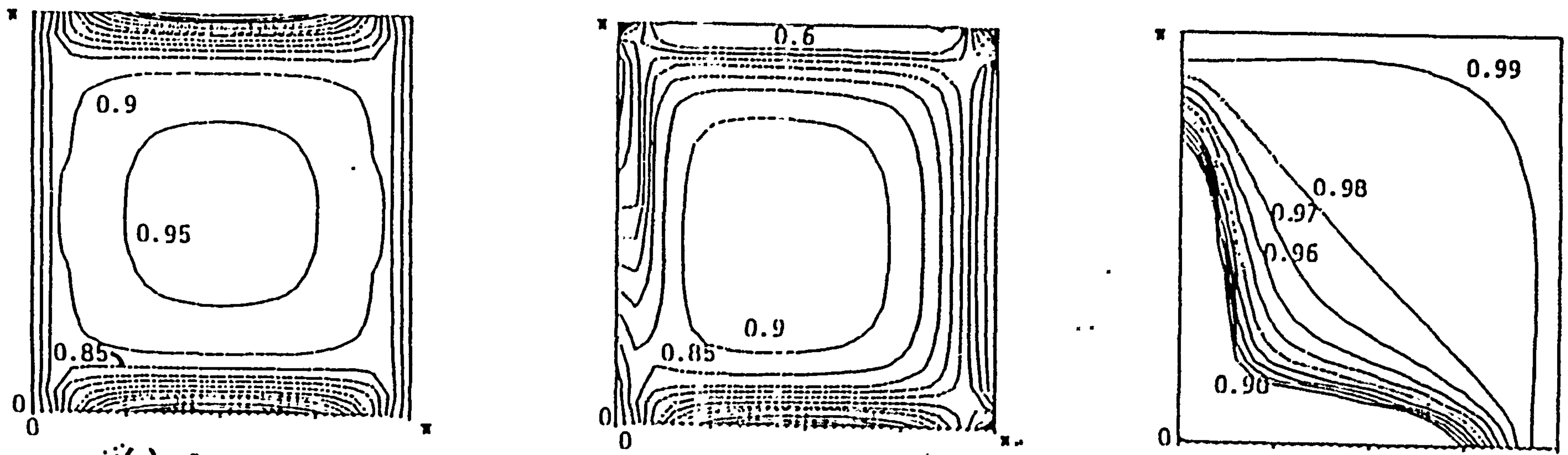
Convergence Rates of Preconditioning Method
for Various Mach Numbers



Convergence for 2-dimensional low Mach number formulation

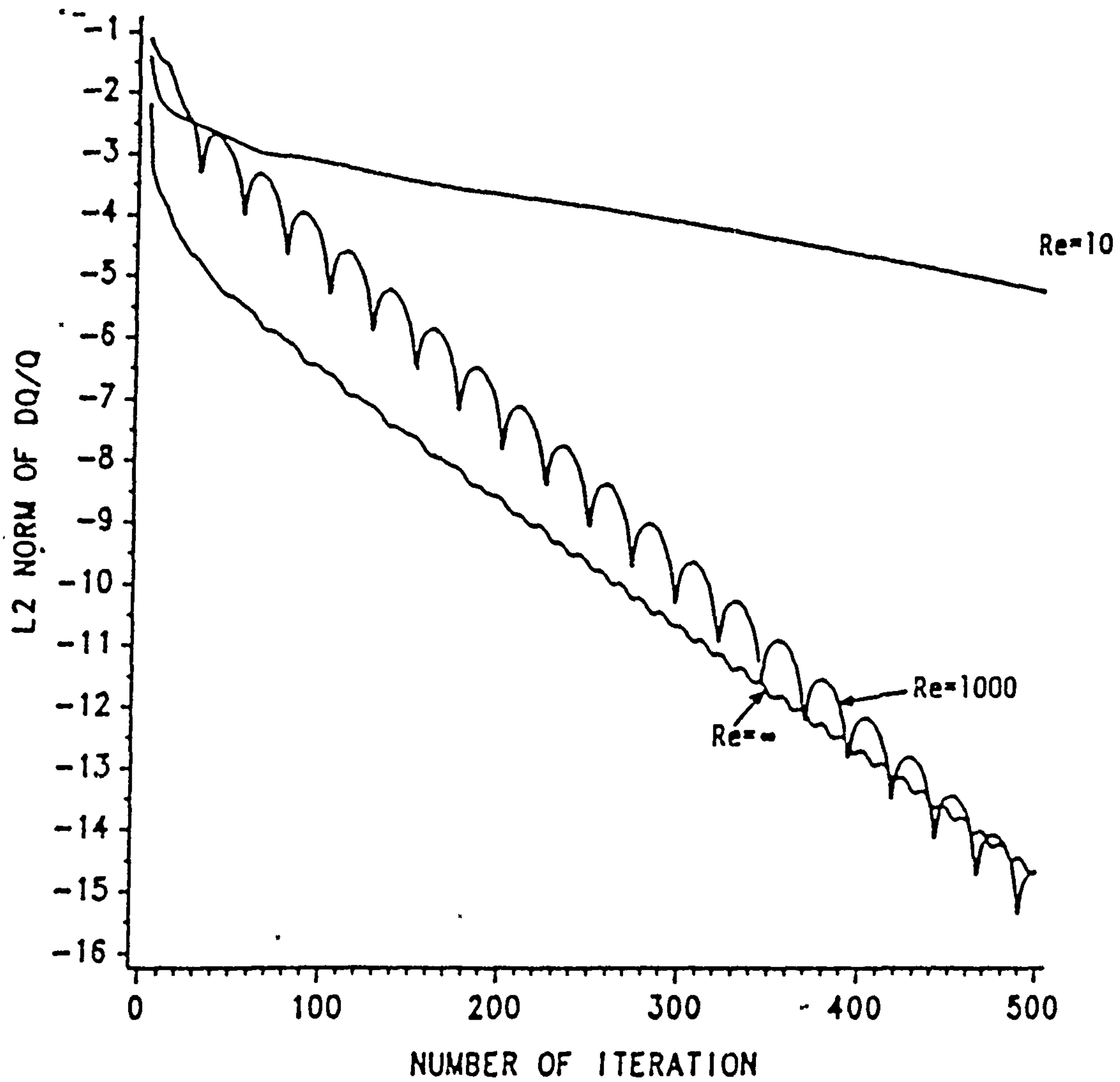
$M = 10^{-5}$

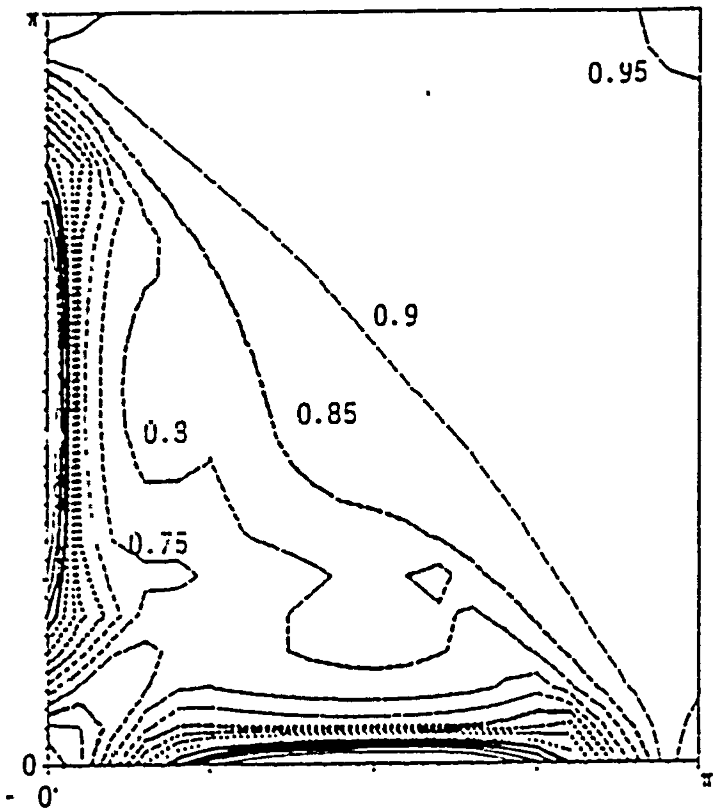




(a) Re=∞ (b) Re=1000 (c) Re=10

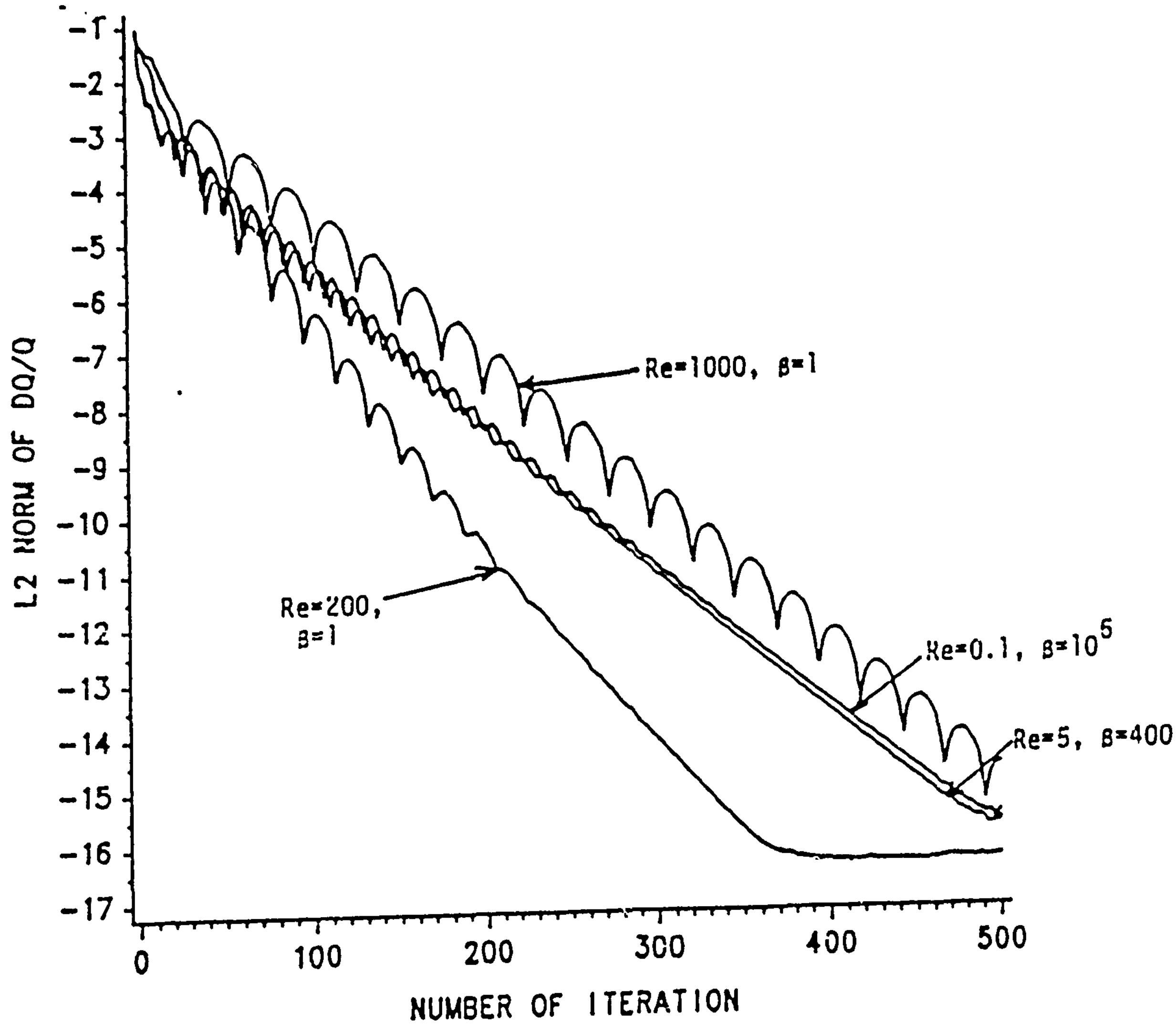
Convergence Rates of Low Mach Number Viscous Formulation for Various Reynolds Numbers



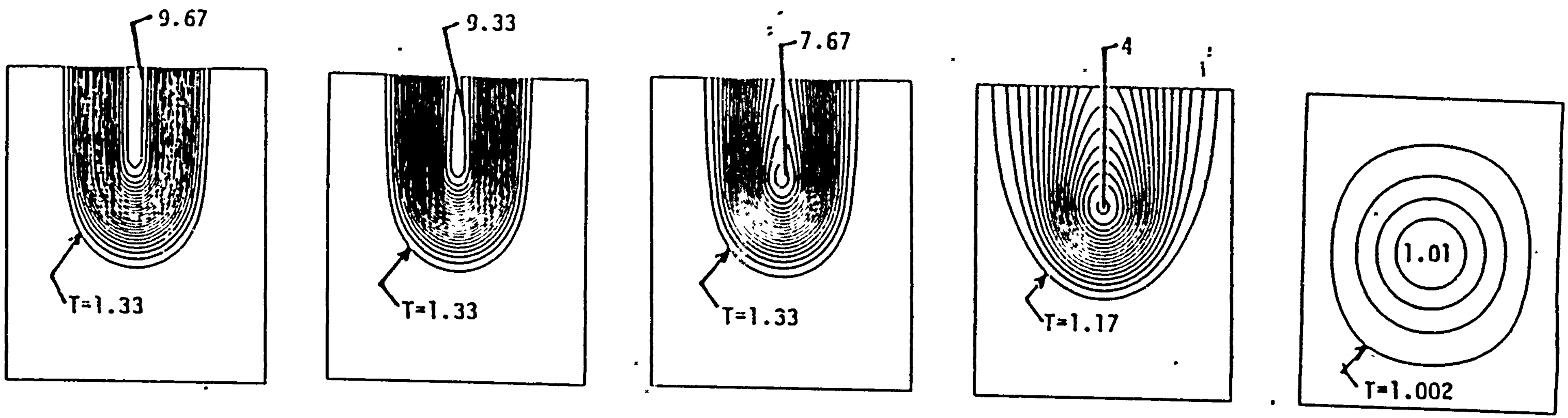


0.95
0.9
0.85
0.3
0.75
0
0

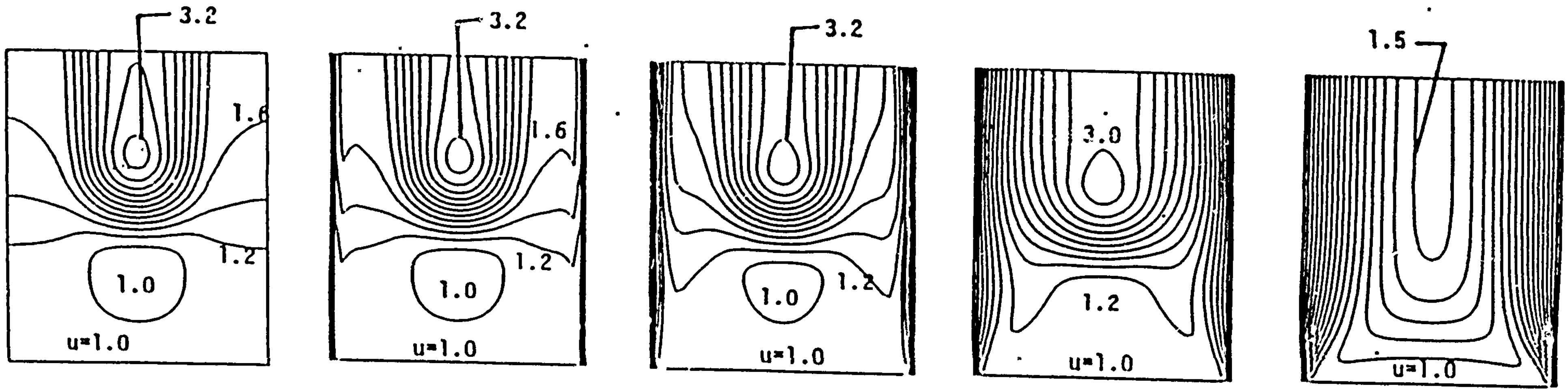
Convergence Rates of Low Mach Number Viscous Formulation
Using Optimum Values of Time-Solving Parameter, β



Flowfield Solutions for Various Reynolds Numbers

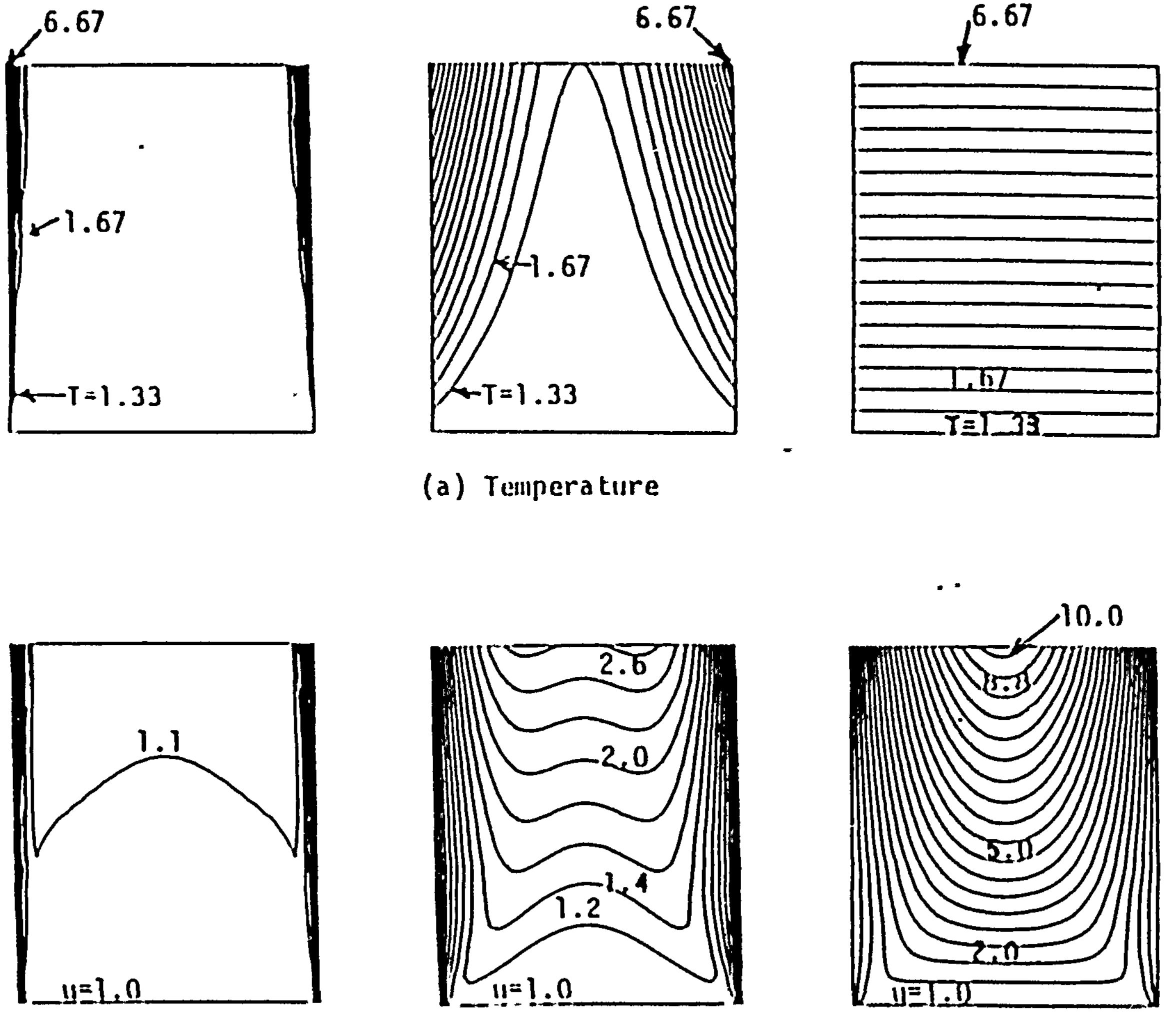


(a) Temperature Contours



(b) Velocity Contours

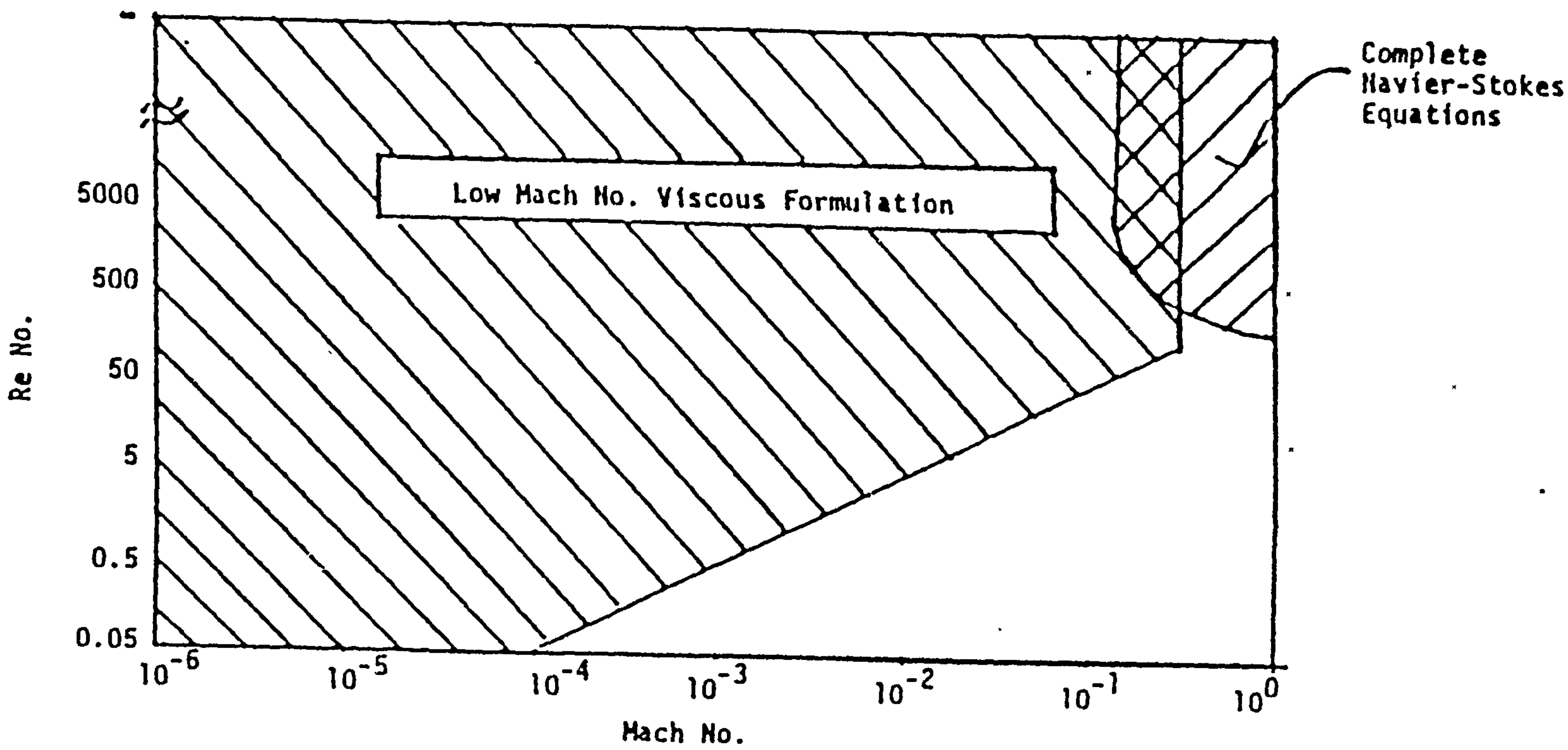
Re=∞, β=1 | Re=5000, β=1 | Re=500, β=1 | Re=50, β=4 | Re=0.05, $\beta=4\times10^{6}$



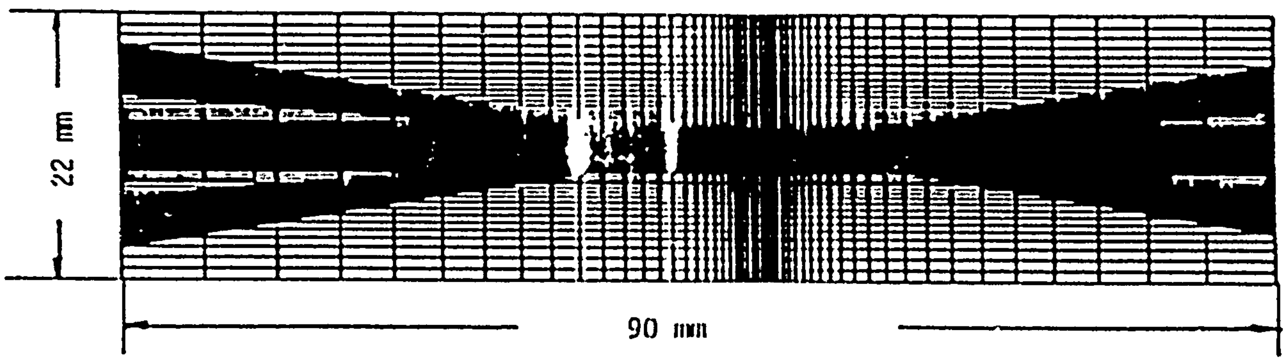
(b) Velocity

Re=5000, β=1 | Re=50, β=4 | Re=0.05, $\beta=4\times10^{6}$

Applicable Flow Regime of Low Mach Number Viscous Formulation



Absorption Chamber Geometry
(51 x 31 Grid)



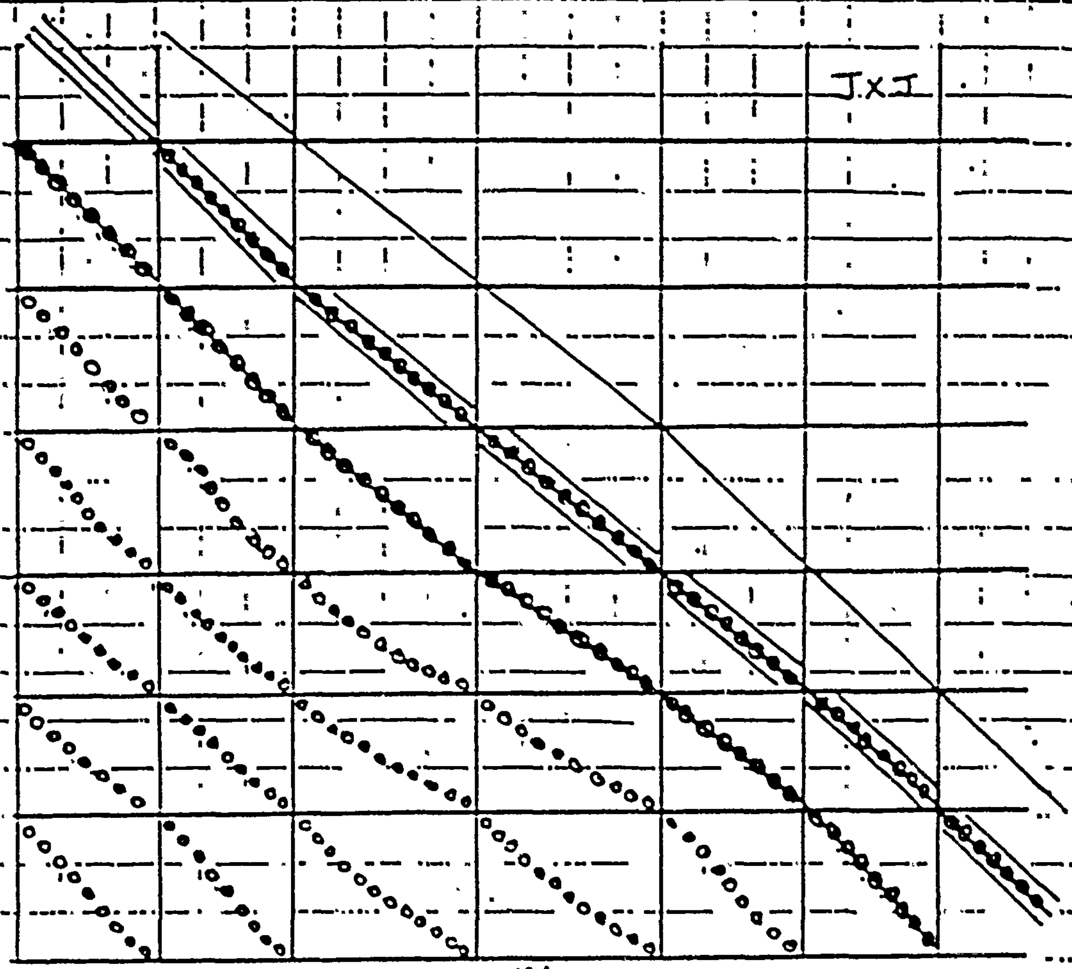
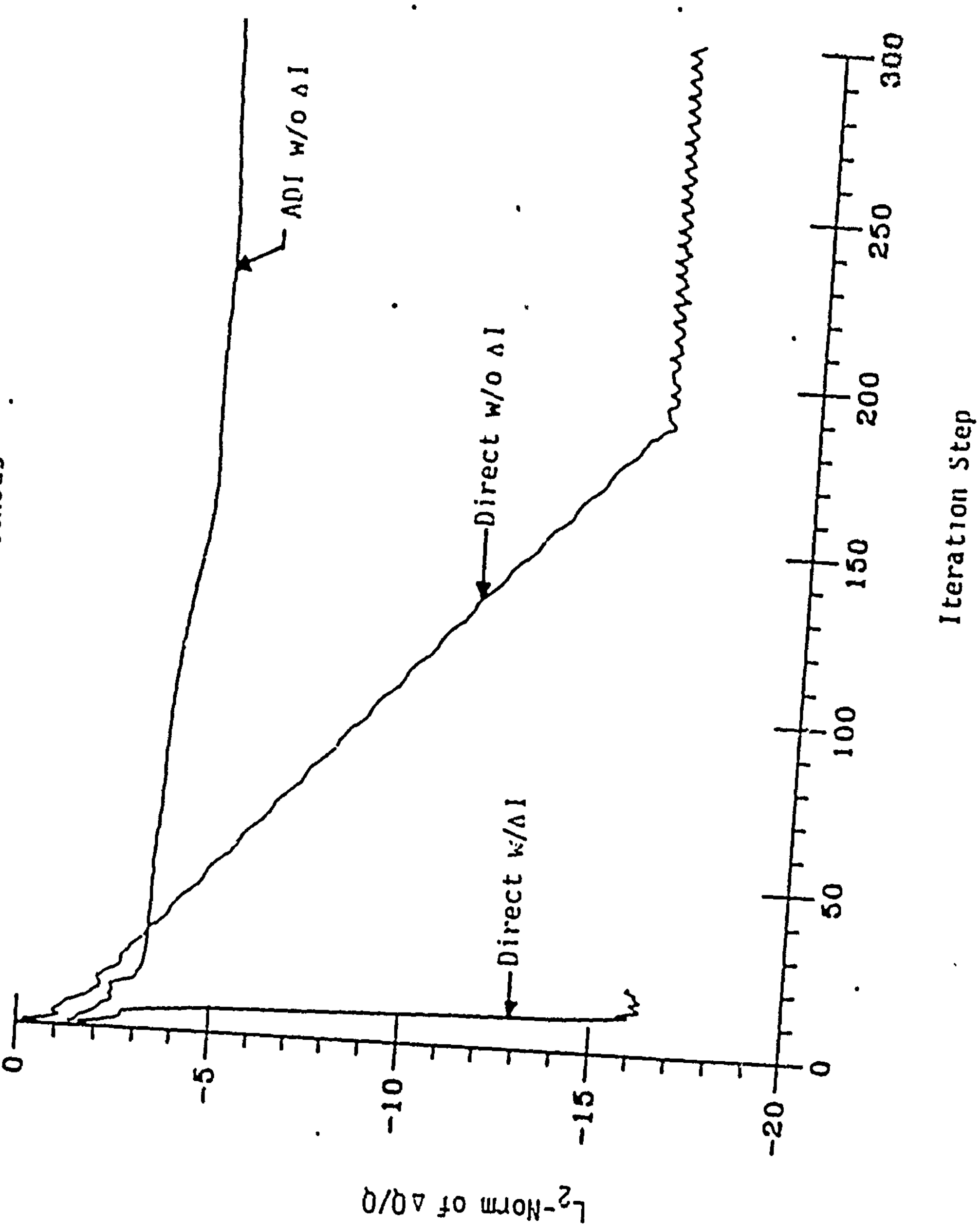
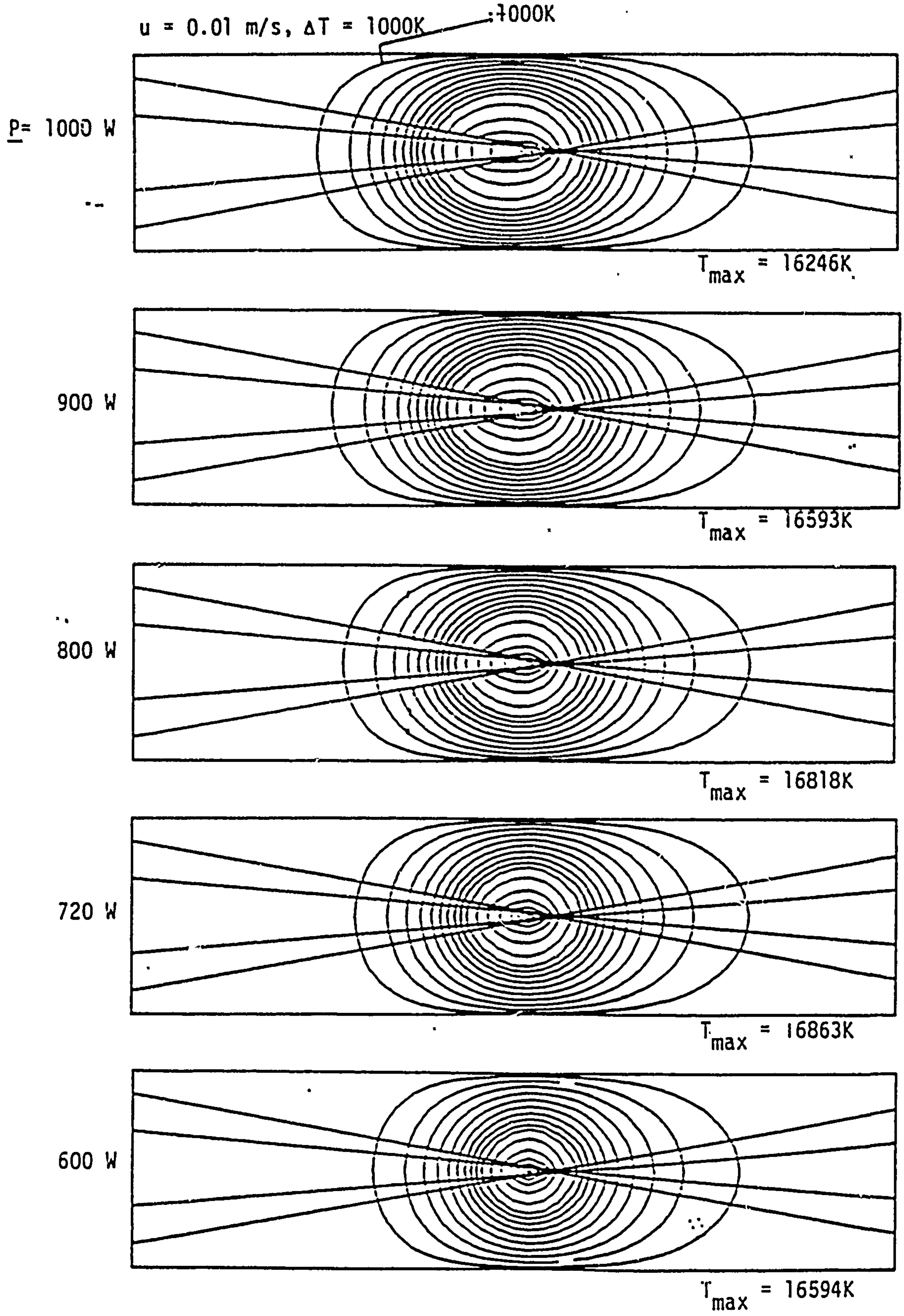


Fig. 1 Matrix Structure for Radiation/Fluids Computation. Lines show regular fluid variables; circles are for radiation intensity.

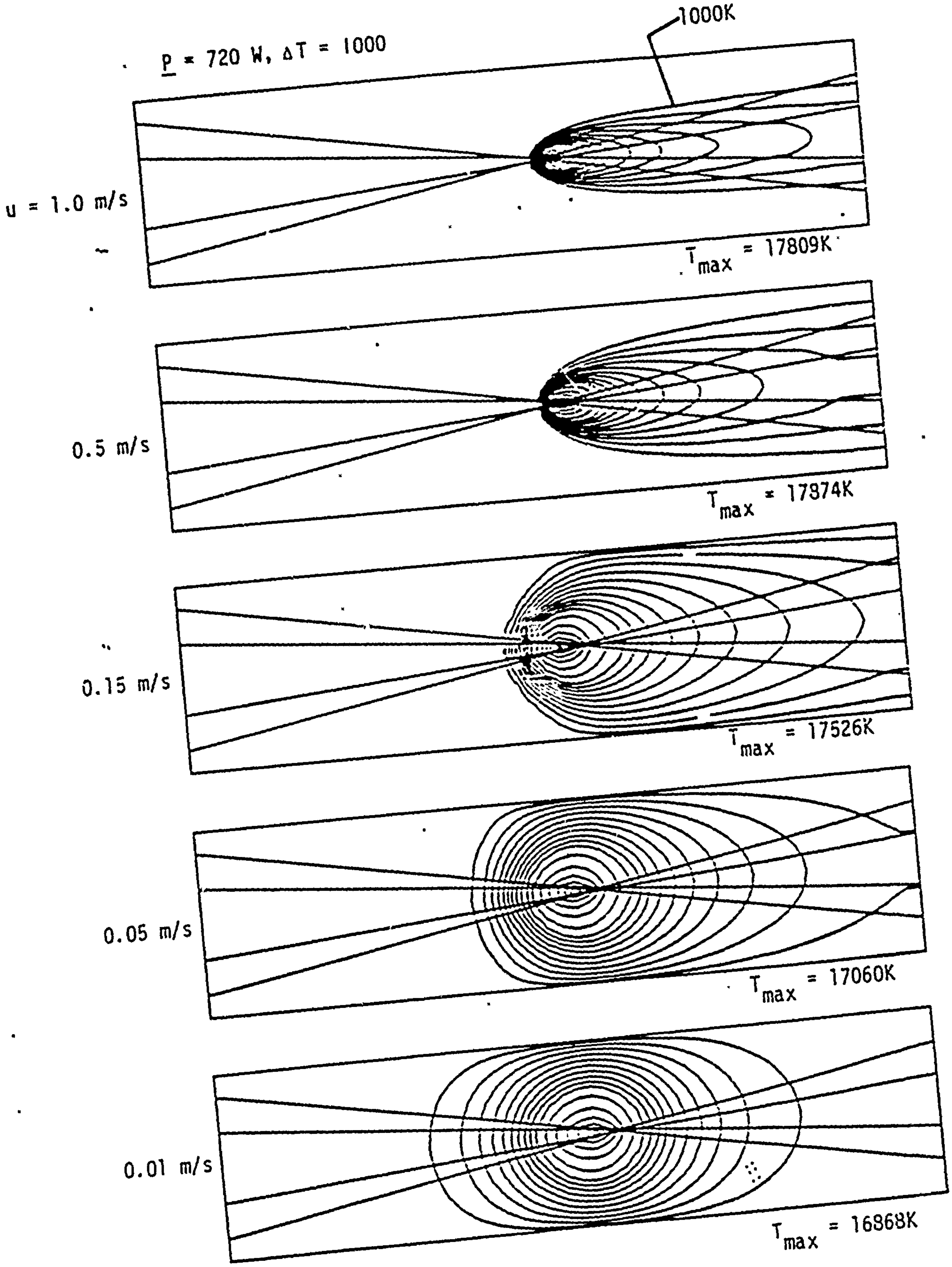


Convergence rates for various numerical methods

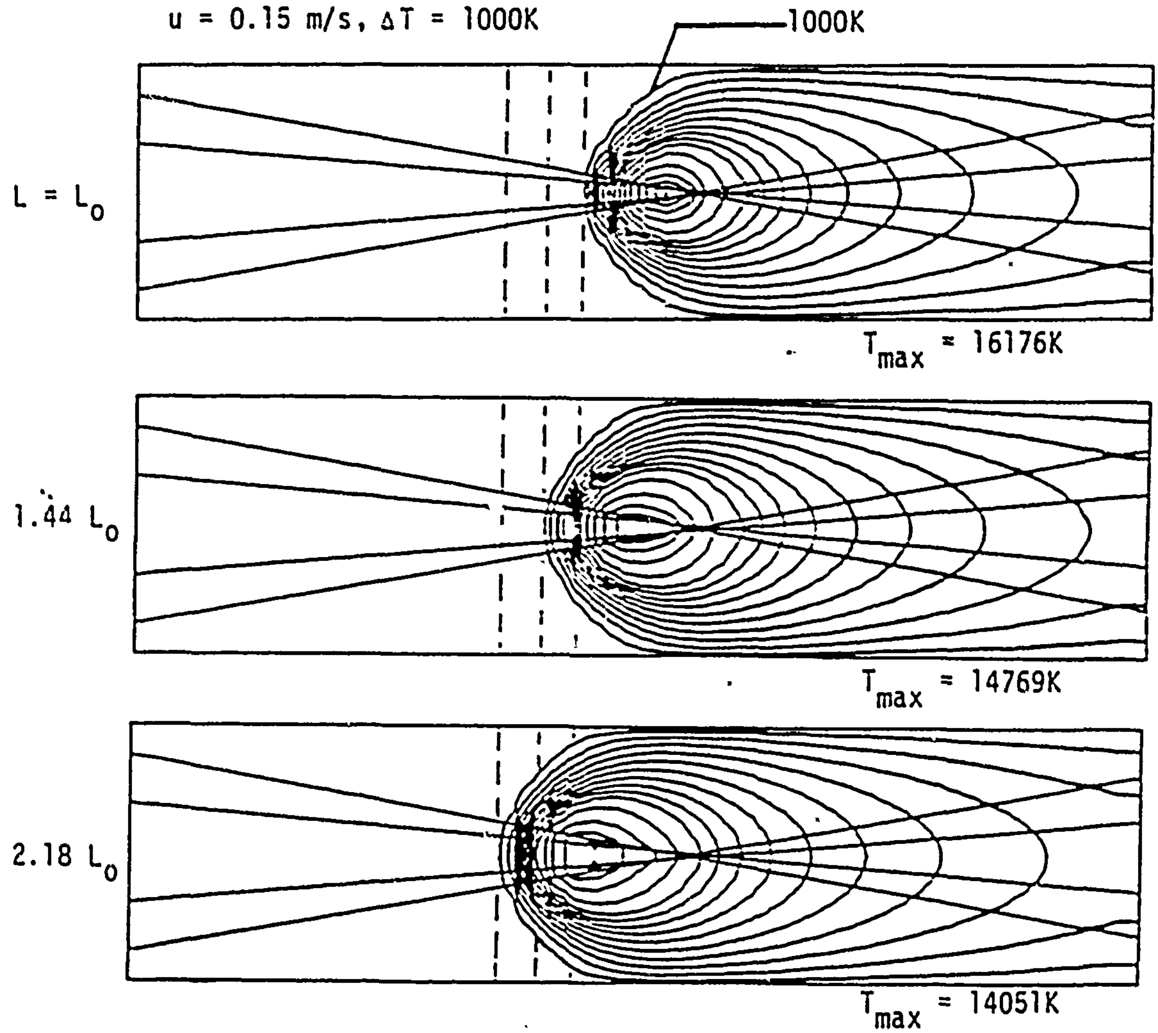
Temperature Field with Laser Power Variation

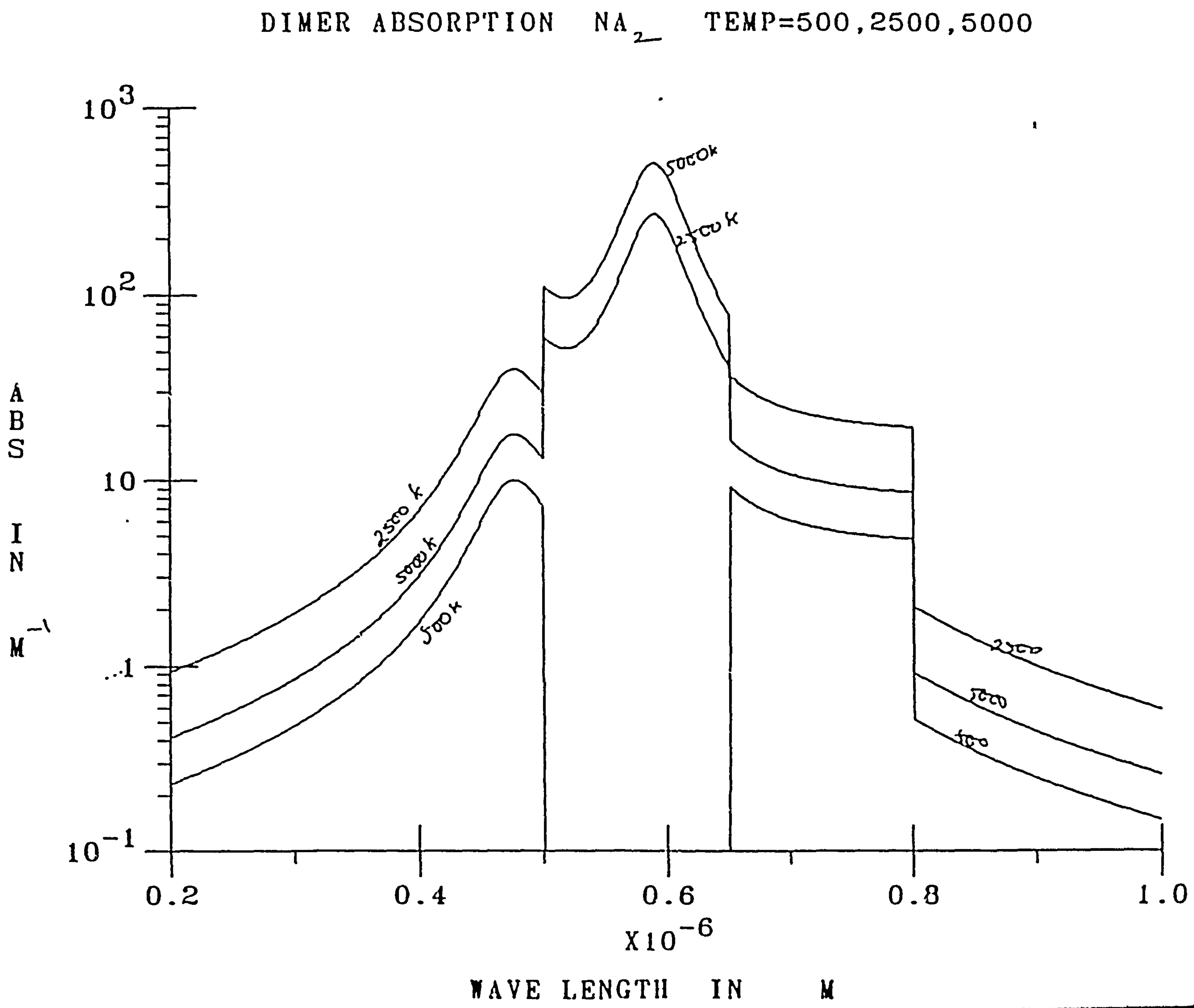


Temperature Field with Velocity Variation

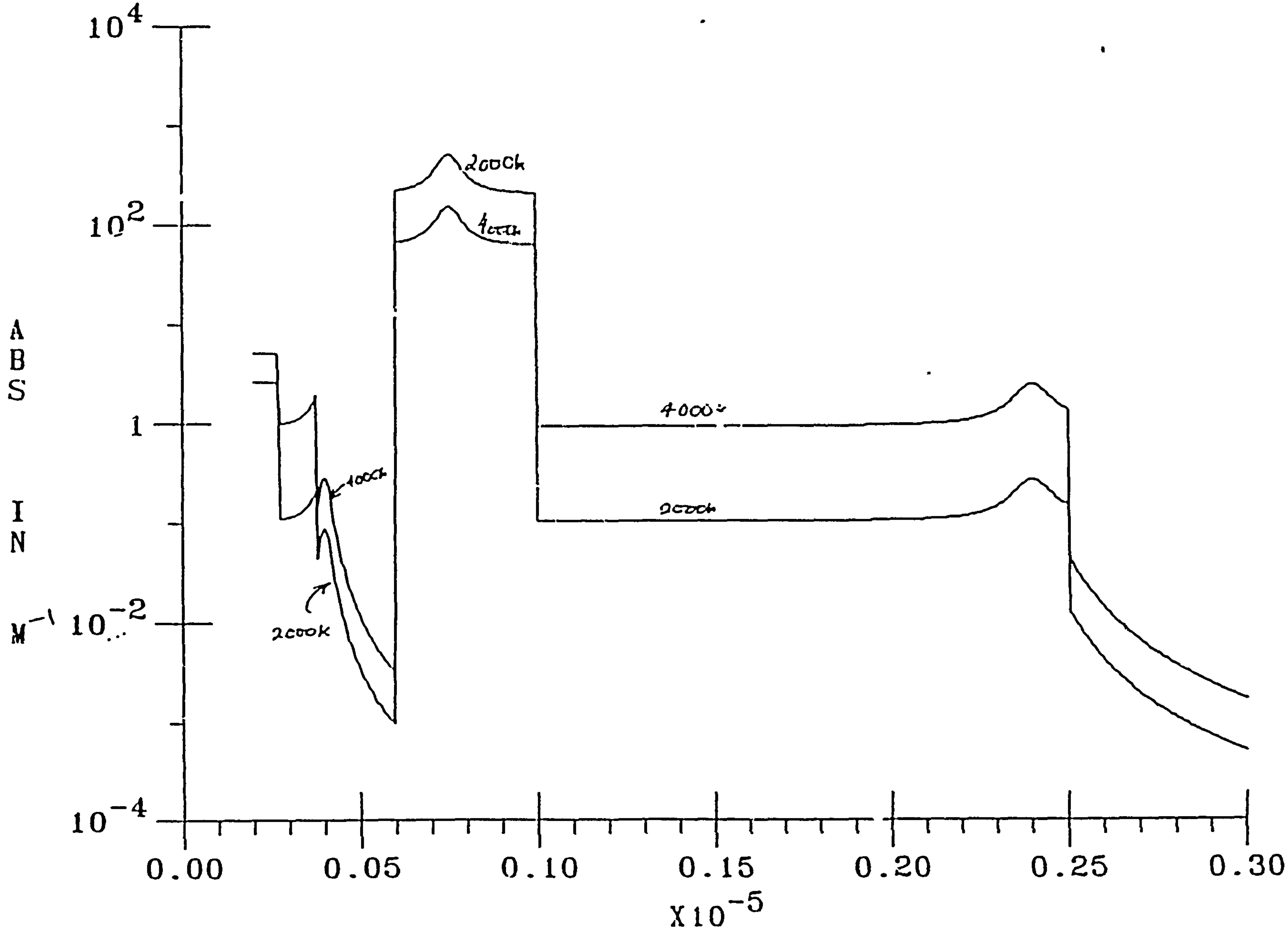


Temperature Field with Chamber Geometry Variation




DIMER ABSORPTION NA2 TEMP=500,2500,5000
10^3
10^2
10
.1
10^-1
ABS IN M^-1
0.2
0.4
0.6
0.8
1.0
X10^-6
WAVE LENGTH IN M
5000K
2500K
2500 K
5000K
500K
2500
5000
500

DIMER ABSORPTION OF K_2 TEMP=2000,4000K



SUMMARY

- TIME-ITERATIVE METHODS HAVE BEEN EXTENDED TO:
  - Low Mach Number Conditions
  - Low Reynolds Number Conditions
  - Rapid Convergence Demonstrated from
    - Inviscid to Re = 0.01
    - Transonic to $M = 10^{-6}$
- GENERALIZED TIME-ITERATIVE ALGORITHM
  - Allows Central Differencing of Convective Terms at All Cell Reynolds Numbers
  - Expressed in Arbitrary Bodyfitted Coordinate System
- APPLICATION TO LASER ABSORPTION CALCULATION
  - Fully Coupled, Fully Implicit Radiation/Gasdynamics
    - Converges to Machine Accuracy in 10-20 Iterations
  - Uncoupled, Fully Implicit Radiation/Gasdynamics
    - Converges in Few Hundred Iterations
  - Uncoupled, Approximate Implicit
    - Converges Slowly
- IMPORTANT PROBLEMS REMAINING
  - Improved Modeling of Radiation Losses
  - Size Scale-up to Large Lasers

LASER PROPULSION WORKSHOP

University of Illinois
February 8-10, 1988

ABSTRACT

San-Mou Jeng

Center for Laser Applications
The University of Tennessee Space Institute
Tullahoma, Tennessee 37388
615 455-0631

This abstract summarizes the results of research efforts over the past two years at UTSI. The objectives of the study were to develop a CFD code in order to improve the understanding of the fundamental physics related to laser-sustained plasmas and to develop a code that could be used for the design of a laser powered rocket. The current status of the CFD code and some important results from application of the code will be briefly discussed. A detailed report on this research can be found in Refs. 1-5.

Current Status of Computer Code.

The two-dimensional, steady-state Navier-Stokes equations for compressible, variable properties flow were used in the analysis. The thermophysical and optical properties incorporated in the calculations were based on local thermodynamic equilibrium (LTE). Geometric optics were used to describe the laser beam which was assumed to consist of a finite number of individual rays. Diffraction due to the lens and refraction of the laser rays through the plasma was neglected. Beer's law was used to calculate the local intensity for each individual ray and the locally absorbed laser power within the plasmas. The thermal radiation heat flux from the plasma was divided into two parts -- optically thin and optically thick limits -- which are based on the optical depth as a function of wavelength and physical size of the plasmas.

The governing equations were first transformed to generalized curvilinear coordinates for numerical calculations. The numerical algorithm is based on PISO method with some modifications. The developed code has the capability to calculate complicated flow regions (recirculating, subsonic and supersonic flows) within a realistic rocket geometry. The extension of this method to transient, three-dimensional flows is straightforward.

CFD Code Verification.

More than 100 cases of calculations have been compared with experimental results obtained at UTSI on laser-sustained plasmas within forced convective argon pipe flows. The CFD code has performed well in predicting plasma sizes and positions, temperature distributions and energy conversion efficiency from laser power to the fluid. In a few cases, the model did not perform well since some of the assumptions were violated. For example, the radiative heat transfer model is not adequate for low pressure plasmas (< 2 atm), and the

diffraction and refraction of the laser beam through the plasma flow may be very important for certain optical arrangements.

Parametric Study of Laser-Sustained Hydrogen Plasmas.

The effect of laser power, wavelength and beam profile, has been investigated using a wide range of optical arrangements for laser-sustained hydrogen plasmas under different forced convective flows. It was found that the plasma behavior (size and position) can be controlled, and the power conversion efficiency can be as great as 60% using high speed (> 60 m/s) incoming flows in conjunction with laser powers greater than 20 kW. It was also found that shorter wavelength lasers (eg. the chemical laser at 2.7 microns) is needed for plasma operation at megawatt power levels in order to control the plasma position near the focal point.

30 kW Rocket Design.

The purpose of this study was to design a prototype thruster supported by a 30 kW, 10.6 micron laser. The ground test for this thruster will be scheduled at some future date. Several thruster designs having different throat sizes and operated at 150 and 300 kPa chamber stagnation pressure were studied. It was found that focusing the laser beam at the throat will yield the best thruster performance, and a properly designed thruster can attain a specific impulse of approximately 1500 secs. The radiative heat loading on the thruster wall was also estimated, and was found to be in the range of that for a conventional chemical rocket.

Overview of CFD Work on Laser Propulsion at UTSI

Presented by: San-Mou Jeng

Outline

1. Model description and numerical method
2. Model verification and parametric study
3. Design of rockets supported by a 30 kW, 10.6μm laser beam
4. Conclusions

GL-0916

DESCRIPTIONS OF MODEL

1. STEADY-STATE, AXISYMMETRIC AND LAMINAR FLOW.
2. FULL TEMPERATURE AND PRESSURE DEPENDENCE FOR THERMOPHYSICAL AND OPTICAL PROPERTIES. (BASED ON LOCAL THERMODYNAMIC EQUILIBRIUM)
3. GEOMETRIC RAY-TRACE OF ACTUAL OPTICAL SYSTEM. (NEGLECTS REFLECTION WITHIN PLASMAS AND DIFFRACTION)
4. THERMAL RADIATION FROM PLASMAS DIVIDED INTO TWO PARTS -- OPTICALLY THIN AND OPTICALLY THICK.
5. ADIABATIC THRUSTER WALL WITH ZERO EMISSIVITY.

Numerical Methods

First Stage: *based on SIMPLE algorithm*

- Recirculating and subsonic flows
- Steady-state application
- Uniform rectangular meshes (staggered grids)
- Unconditionally stable with adequate underrelaxation

Second Stage: *based on PISO algorithm*

- Recirculating, subsonic and supersonic flows
- Steady-state application but can be extended to the transient calculation
- Body-fitted meshes (normal grids)
- Unconditionally stable with adequate underrelaxation

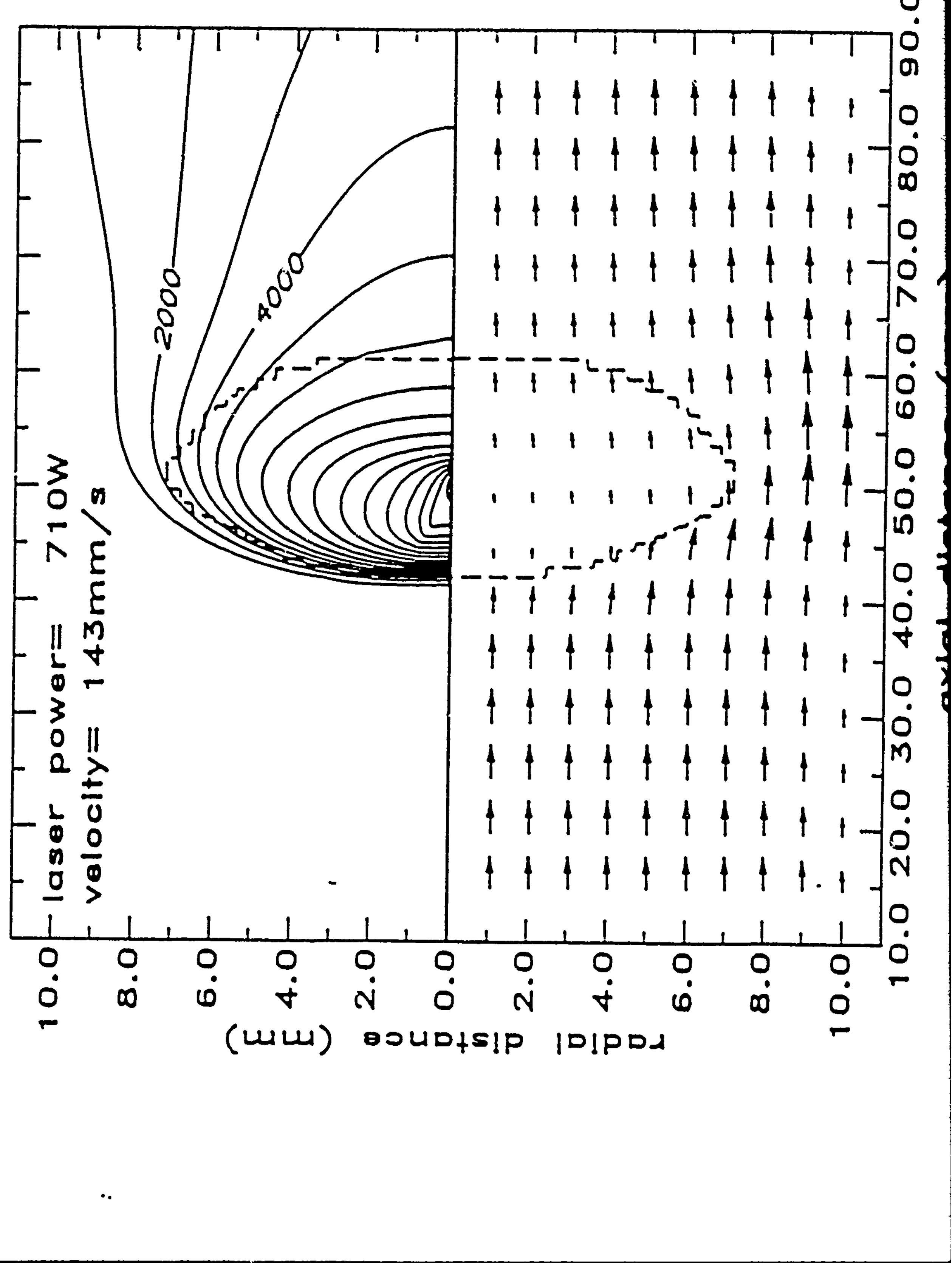
GL-0917

Model Evaluation

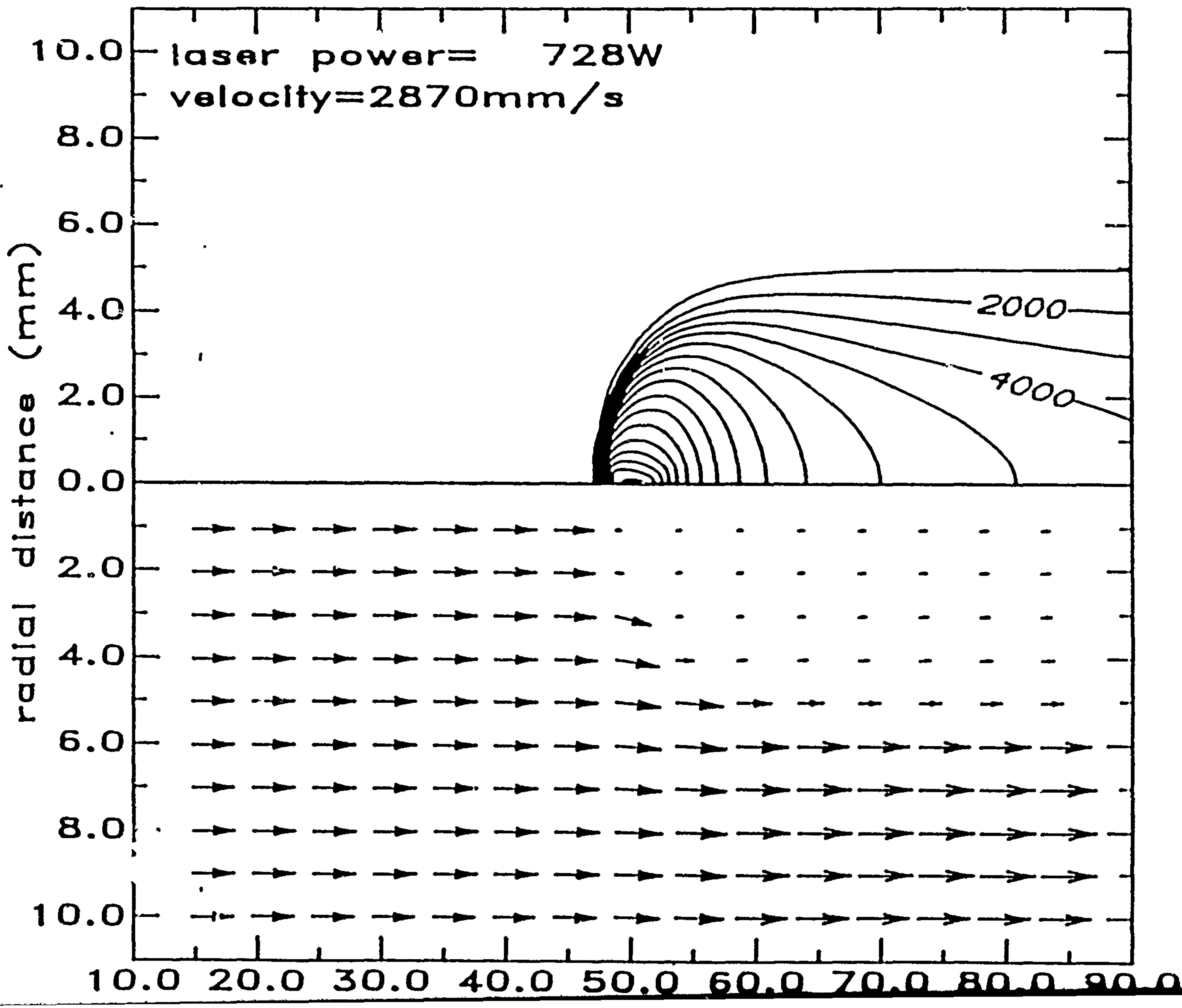
LSP data in forced convective argon flows acquired at UTSI was used to evaluate the model's performance. Parametric studies were also performed considering the following variations:

- Inlet velocity
- Pressure
- Mode of unfocused laser beam
- Focusing lens arrangement

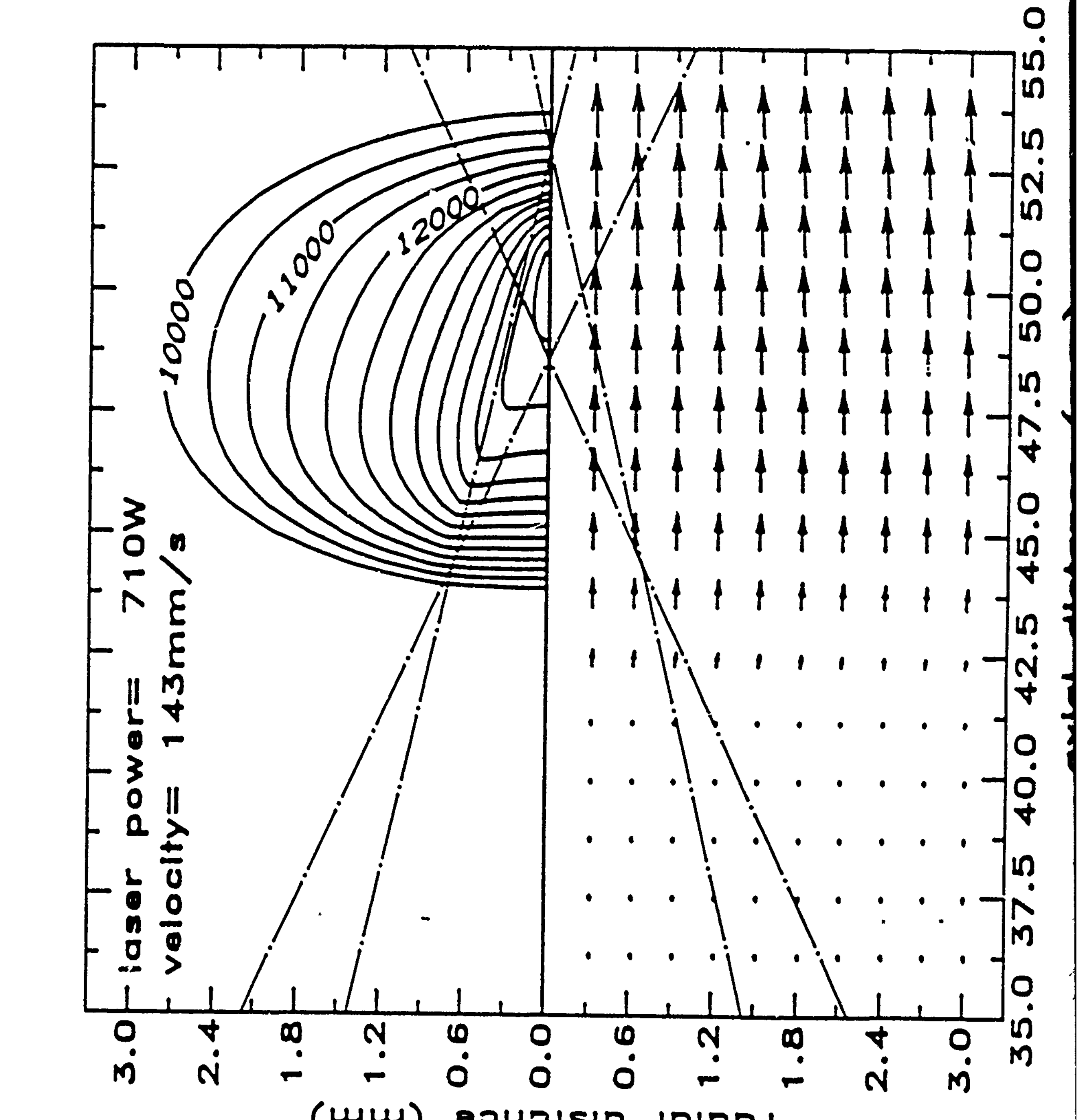
GL-0918

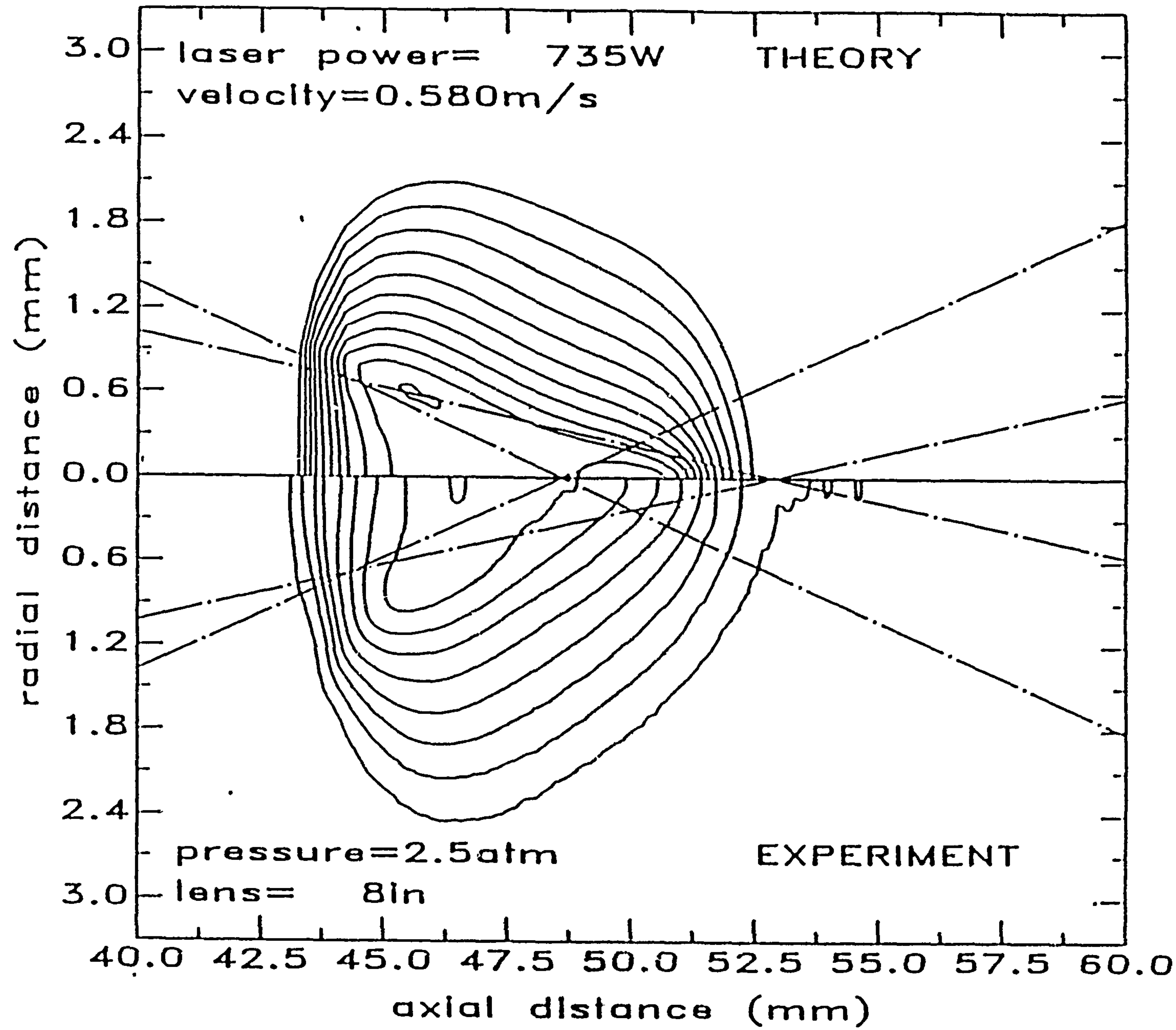


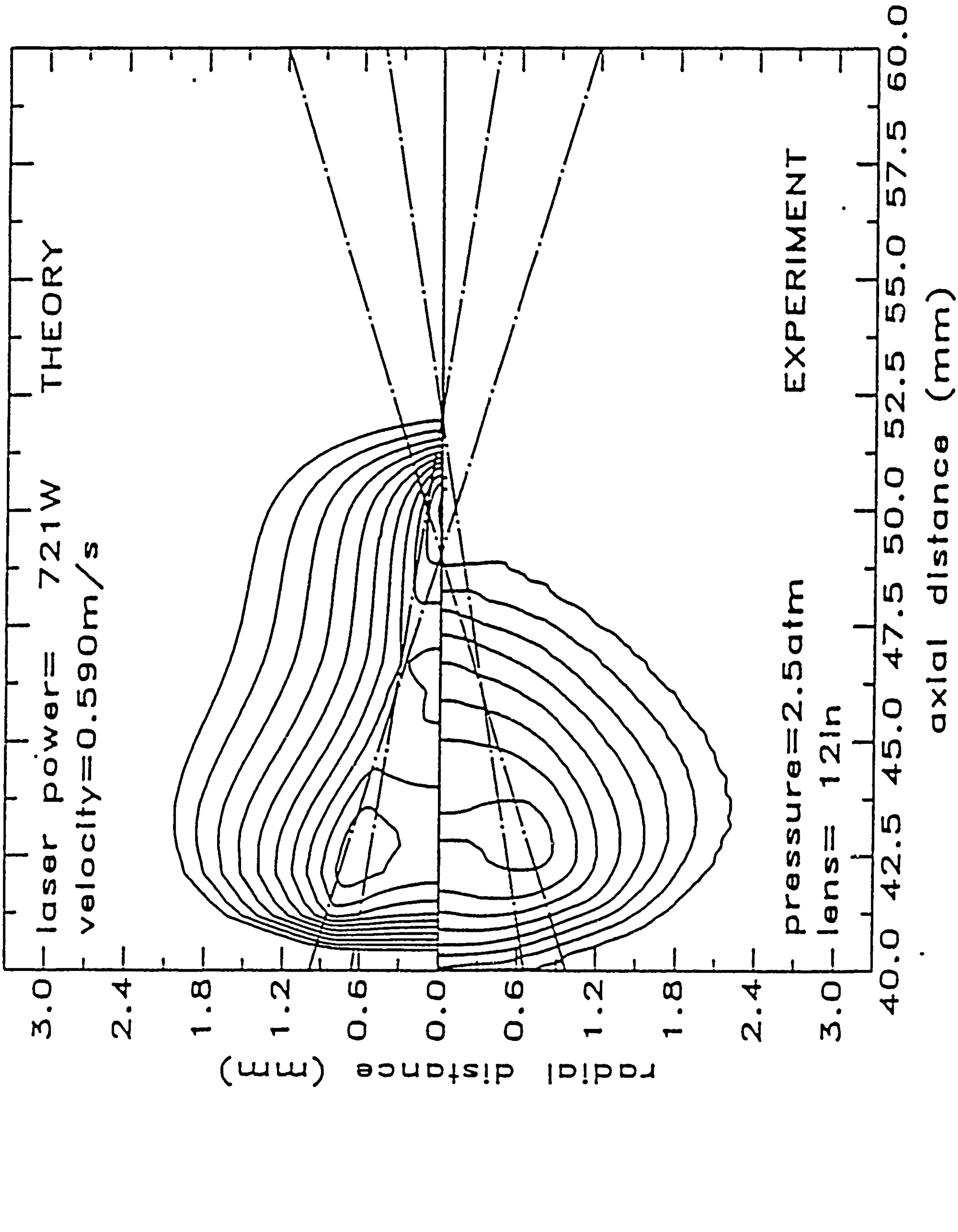
laser power= 710W
velocity= 143mm/s
2000
4000
radial distance (mm)
10.0
8.0
6.0
4.0
2.0
0.0
2.0
4.0
6.0
8.0
10.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0

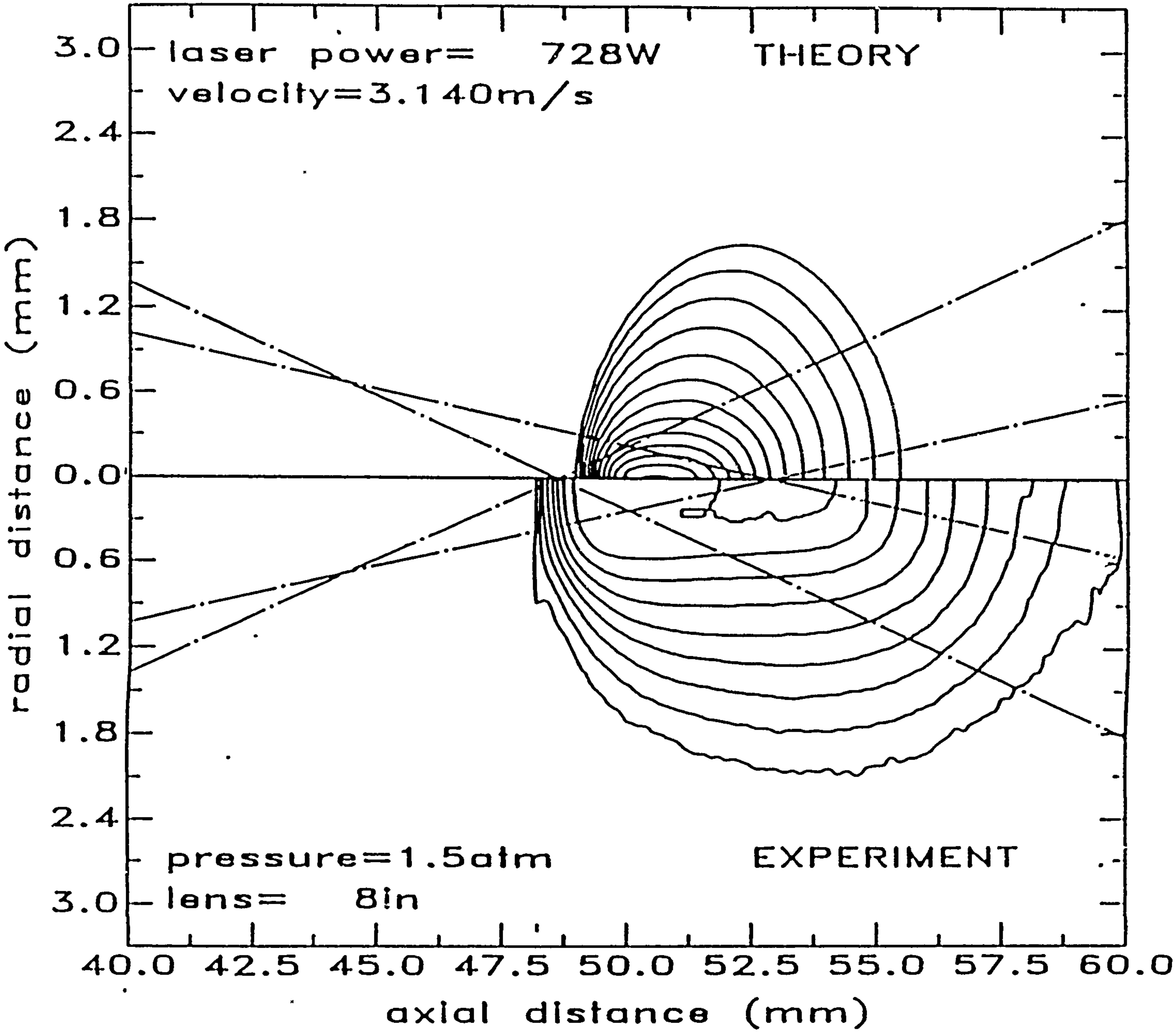


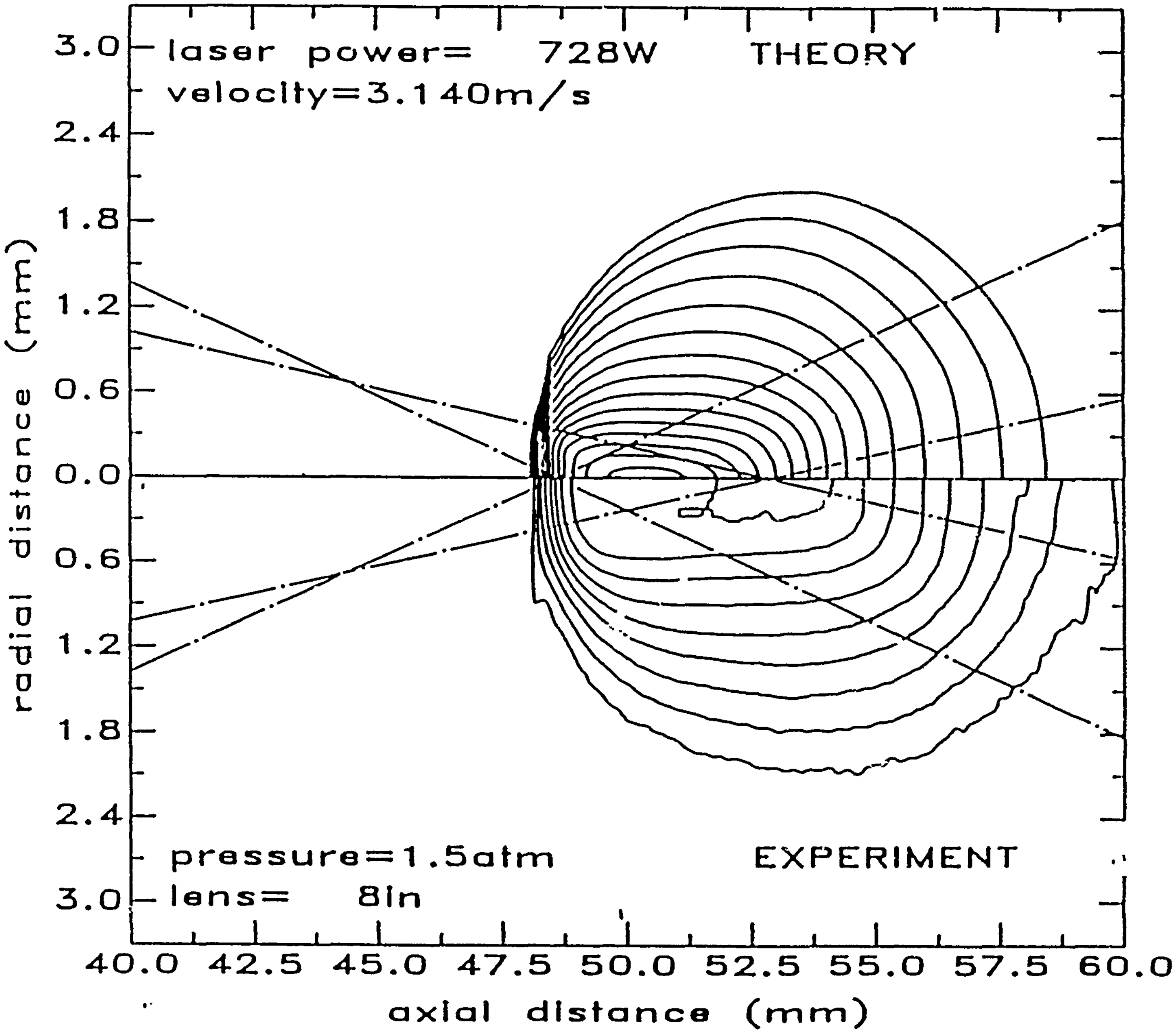
laser power= 728W
velocity=2870mm/s
2000
4000
radial distance (mm)
10.0
8.0
6.0
4.0
2.0
0.0
2.0
4.0
6.0
8.0
10.0
10.0 20.0 30.0 40.0 50.0 60.0 70.0 80.0 90.0


laser power= 710W
velocity= 143mm/s
10000
11000
12000
3.0
2.4
1.8
1.2
0.6
0.0
0.6
1.2
1.8
2.4
3.0
radial distance (mm)
35.0
37.5
40.0
42.5
45.0
47.5
50.0
52.5
55.0


laser power= 735W
velocity=0.580m/s
THEORY
pressure=2.5atm
lens= 8in
EXPERIMENT
3.0
2.4
1.8
1.2
0.6
0.0
0.6
1.2
1.8
2.4
3.0
radial distance (mm)
40.0
42.5
45.0
47.5
50.0
52.5
55.0
57.5
60.0
axial distance (mm)


laser power= 721W
velocity=0.590m/s
THEORY
EXPERIMENT
pressure=2.5atm
lens= 12in
radial distance (mm)
3.0
2.4
1.8
1.2
0.6
0.0
0.6
1.2
1.8
2.4
3.0
axial distance (mm)
40.0
42.5
45.0
47.5
50.0
52.5
55.0
57.5
60.0


laser power= 728W
THEORY
velocity=3.140m/s
pressure=1.5atm
lens= 8in
EXPERIMENT
3.0
2.4
1.8
1.2
0.6
0.0
0.6
1.2
1.8
2.4
3.0
radial distance (mm)
40.0
42.5
45.0
47.5
50.0
52.5
55.0
57.5
60.0
axial distance (mm)

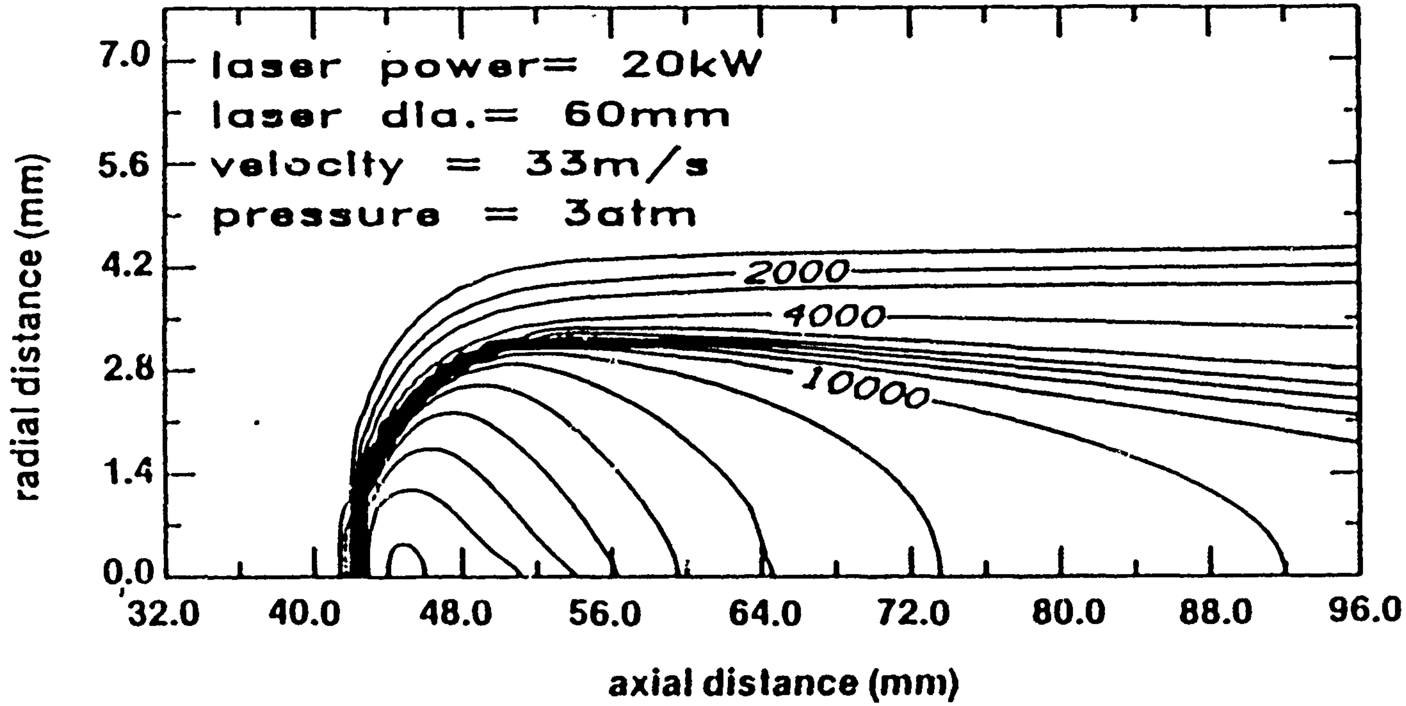


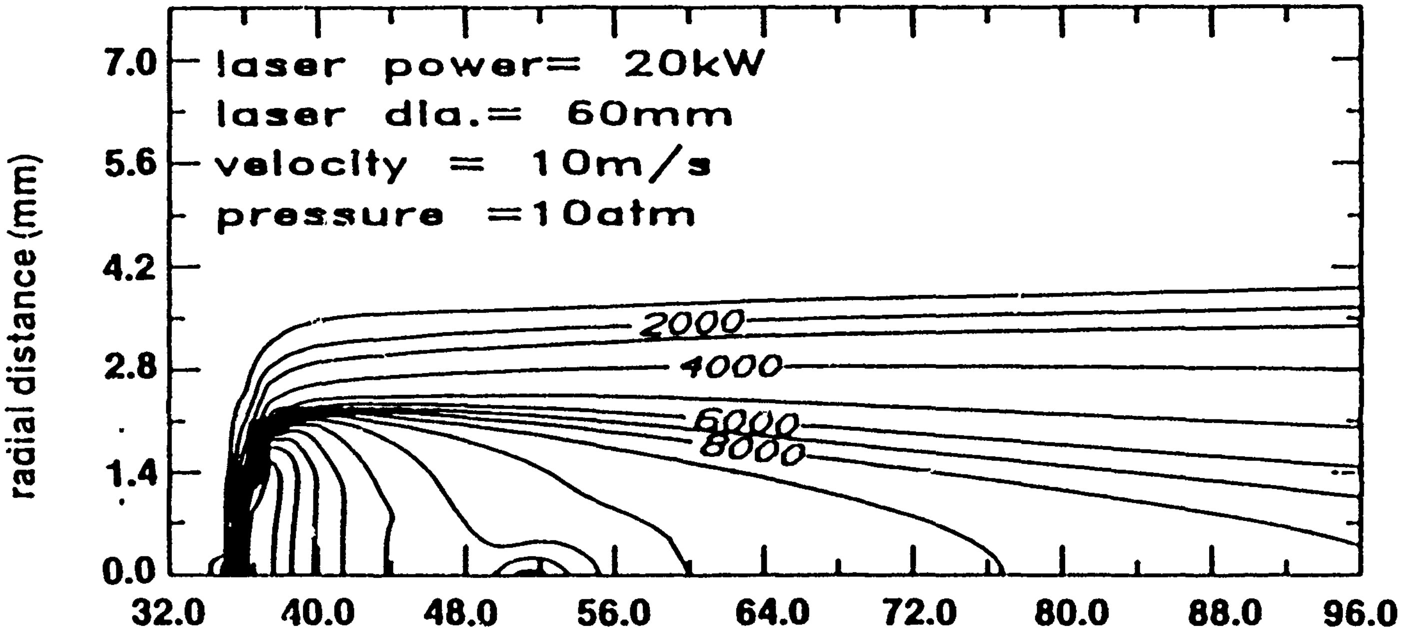
laser power= 728W
velocity=3.140m/s
THEORY
pressure=1.5atm
lens= 8in
EXPERIMENT
3.0
2.4
1.8
1.2
0.6
0.0
0.6
1.2
1.8
2.4
3.0
radial distance (mm)
40.0
42.5
45.0
47.5
50.0
52.5
55.0
57.5
60.0
axial distance (mm)

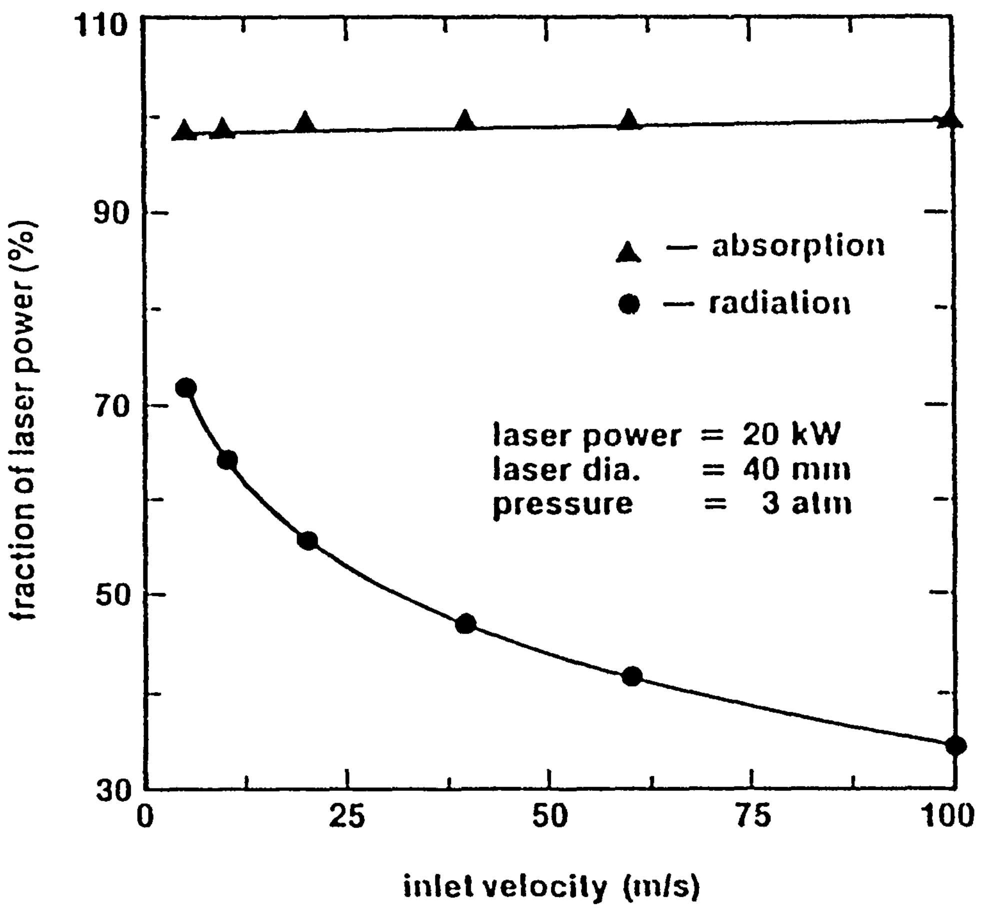
Parametric Study

- Extend the model for LSP in hydrogen flows
- Explore the LSP region beyond the current experimental capability
- Acquire the preliminary information required for the design of laser-supported rockets
- Study the LSP behavior over a wide range of conditions
  - High velocity
  - Available high power lasers
  - Hydrogen plasma

GL-0919


laser power= 20kW
laser dia.= 60mm
velocity = 33m/s
pressure = 3atm
2000
4000
10000
radial distance (mm)
7.0
5.6
4.2
2.8
1.4
0.0
32.0
40.0
48.0
56.0
64.0
72.0
80.0
88.0
96.0
axial distance (mm)

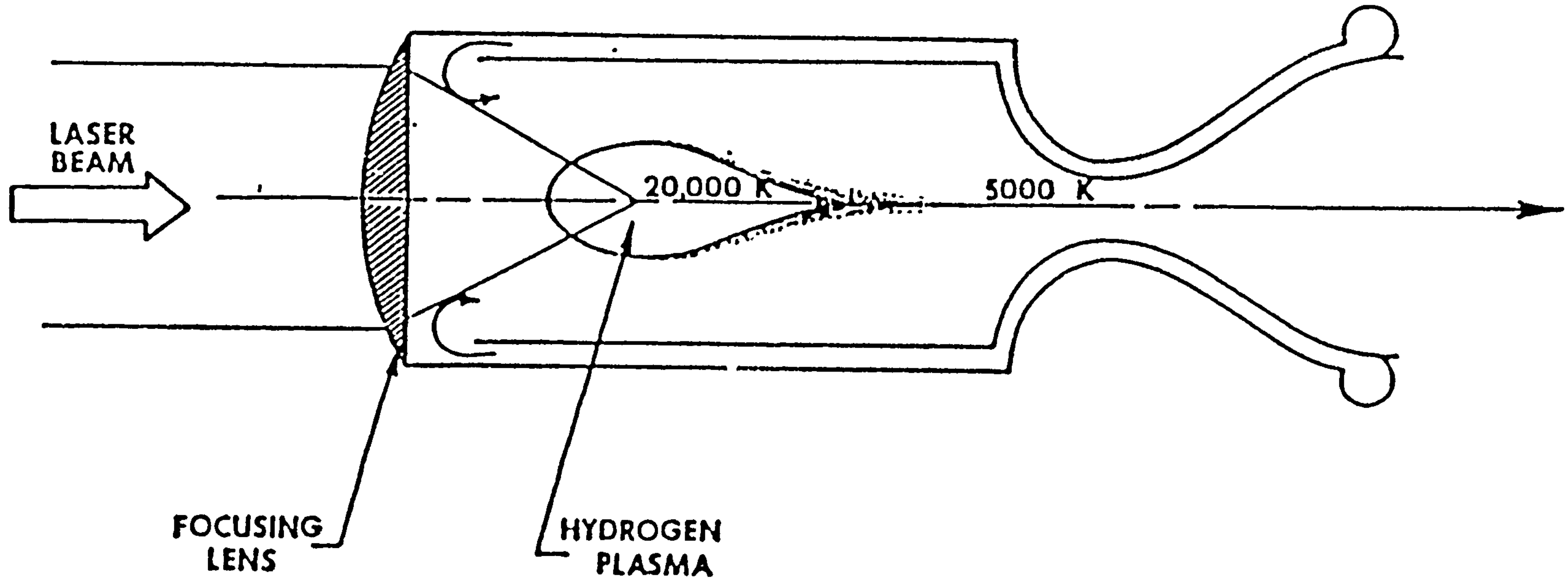

laser power= 20kW
laser dia.= 60mm
velocity = 10m/s
pressure =10atm
2000
4000
6000
8000
radial distance (mm)
7.0
5.6
4.2
2.8
1.4
0.0
32.0
40.0
48.0
56.0
64.0
72.0
80.0
88.0
96.0


110
90
70
50
30
0
25
50
75
100
fraction of laser power (%)
inlet velocity (m/s)
— absorption
— radiation
laser power = 20 kW
laser dia. = 40 mm
pressure = 3 atm

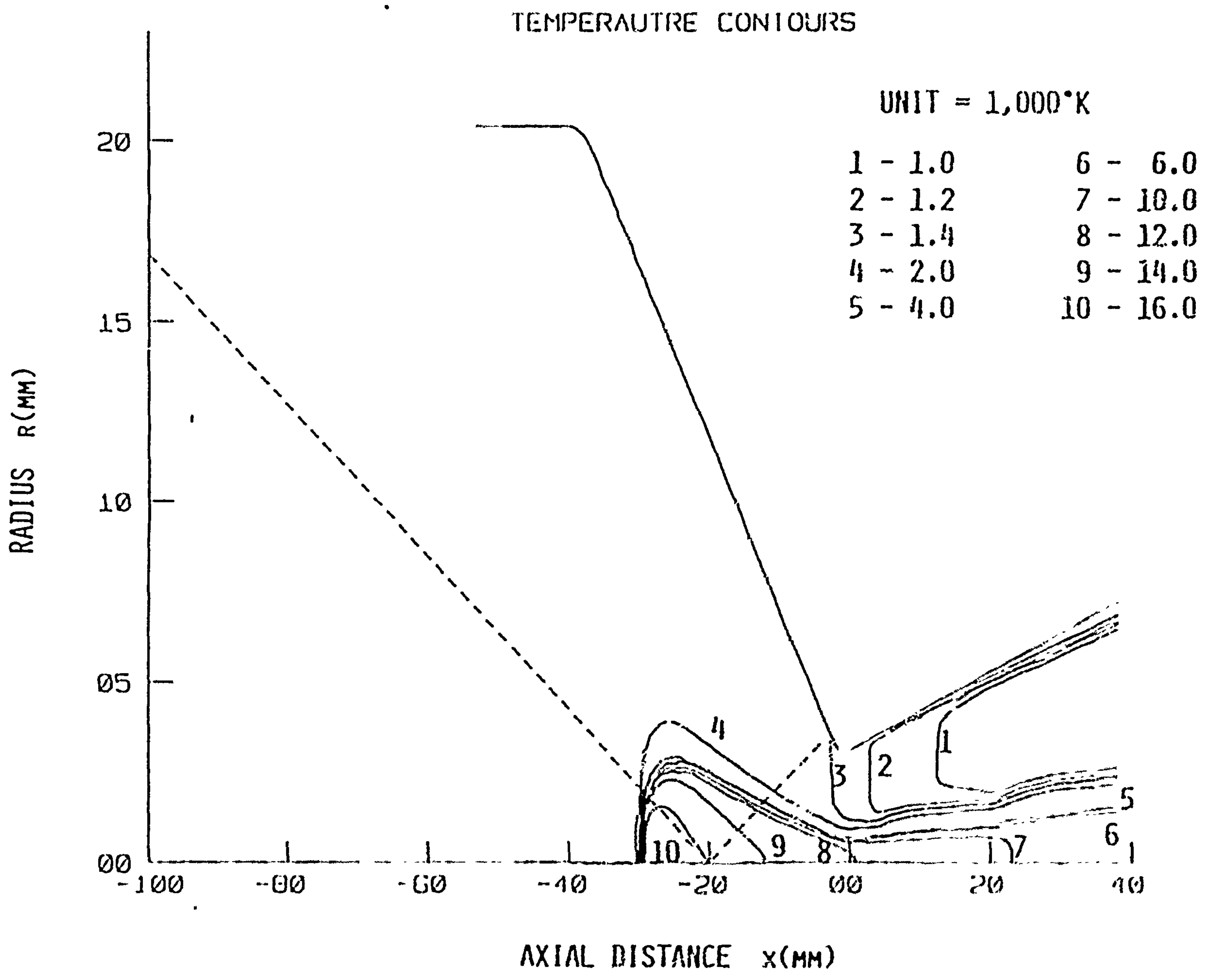
30 kW CO_2 Laser Rocket Design

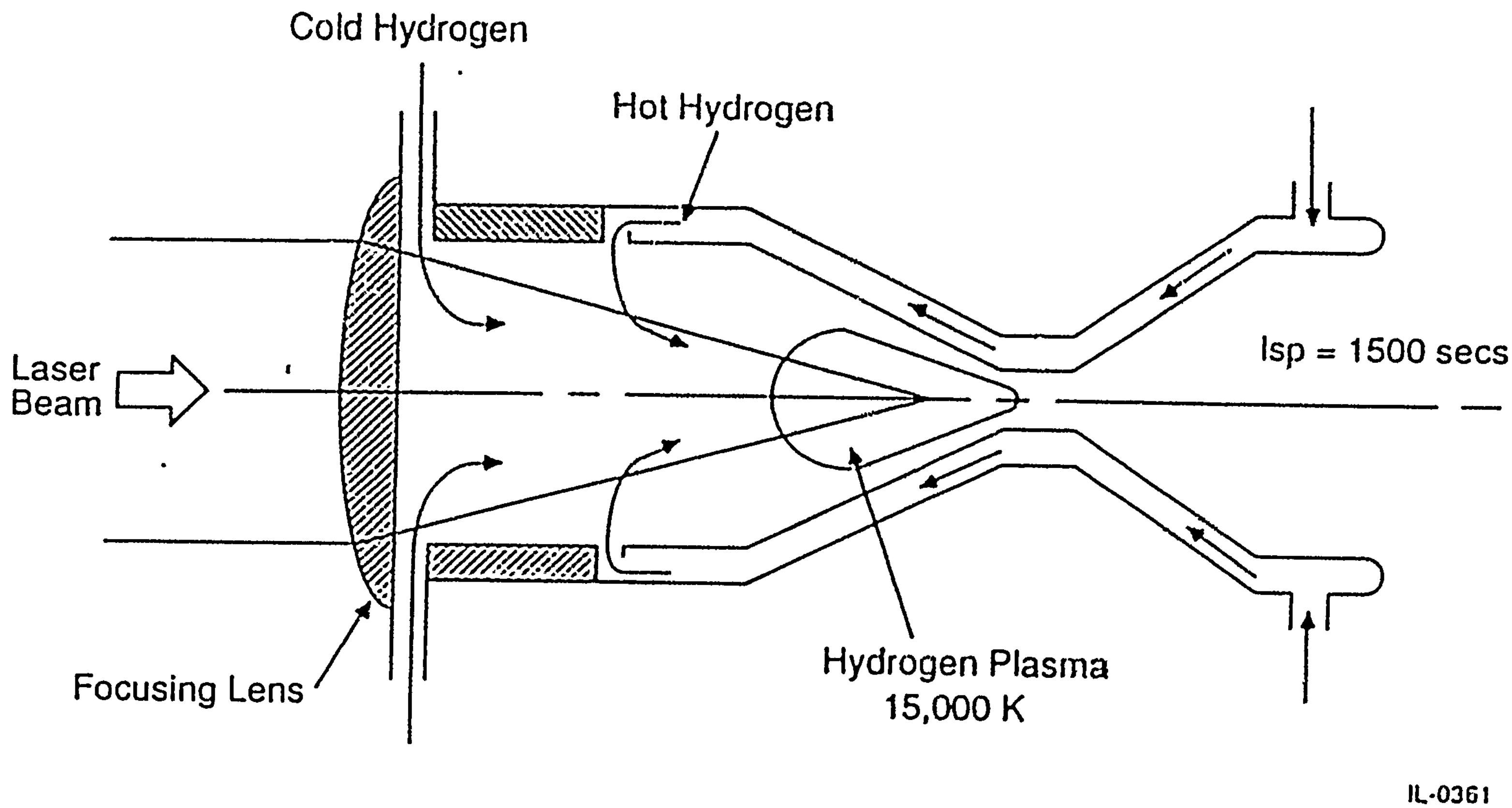
- Where is the best plasma position within the absorption chamber?
- Do we want uniformly distributed propellant temperature across the throat radius?
- What is the level of heat loading on the thruster wall?
- What is the expected laser-supported rocket performance?
- Is finite rate chemistry important to the expected rocket performance?
- What is the best configuration for these rockets?

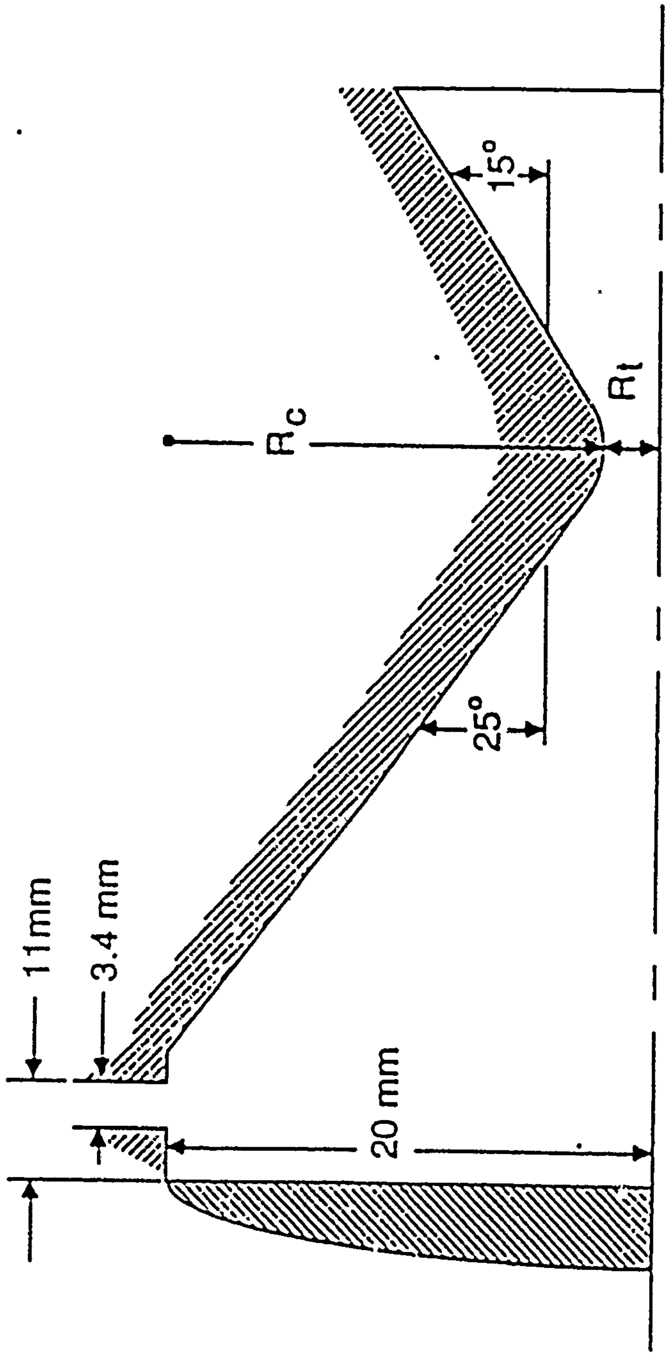
GL-0920



LASER
BEAM
20,000 K
5000 K
FOCUSING
LENS
HYDROGEN
PLASMA

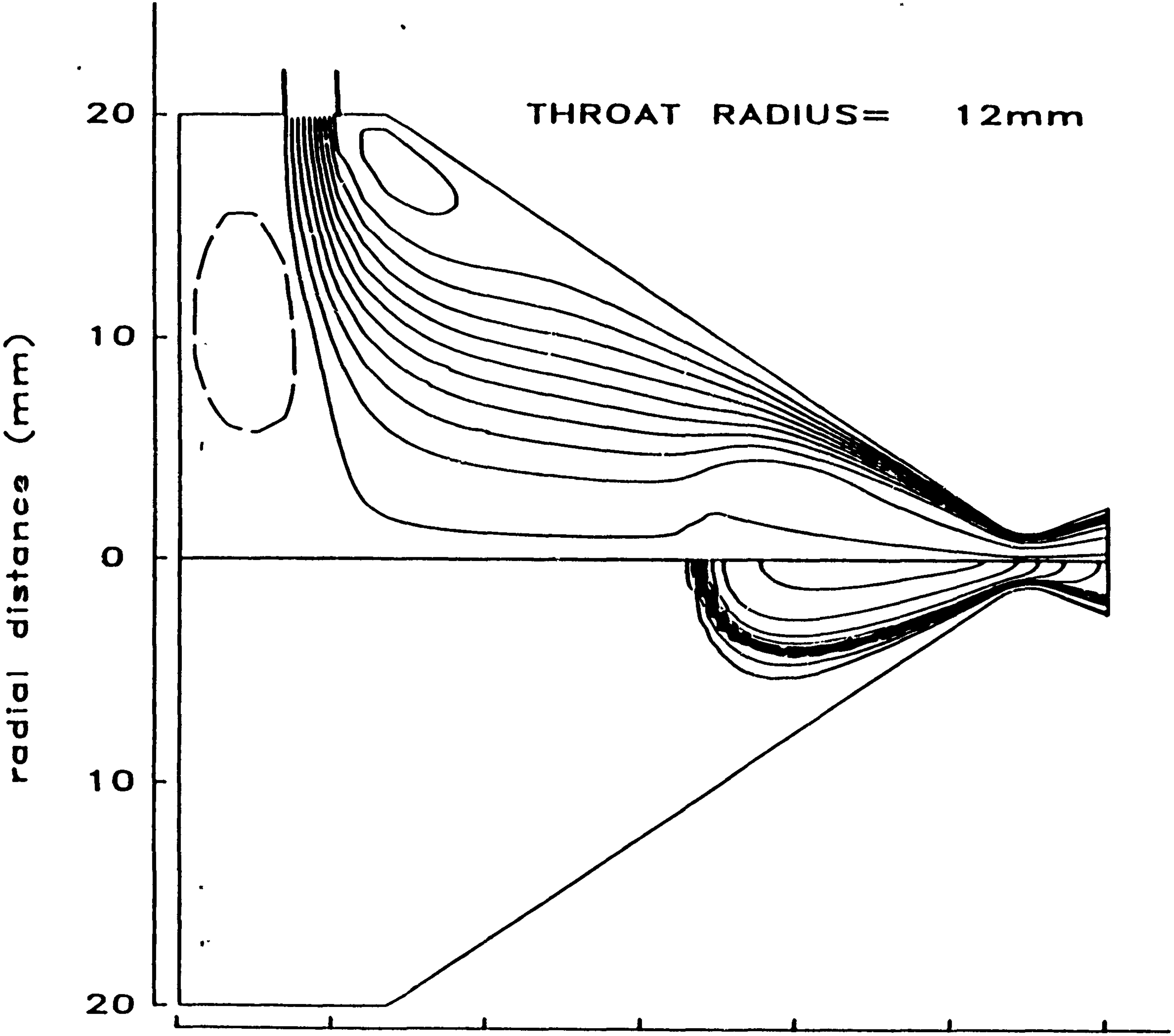

TEMPERAUTRE CONTOURS
UNIT = 1,000°K
1 - 1.0
2 - 1.2
3 - 1.4
4 - 2.0
5 - 4.0
6 - 6.0
7 - 10.0
8 - 12.0
9 - 14.0
10 - 16.0
RADIUS R(MM)
20
15
10
05
00
-100
-80
-60
-40
-20
00
20
40
AXIAL DISTANCE X(MM)
1
2
3
4
5
6
7
8
9
10

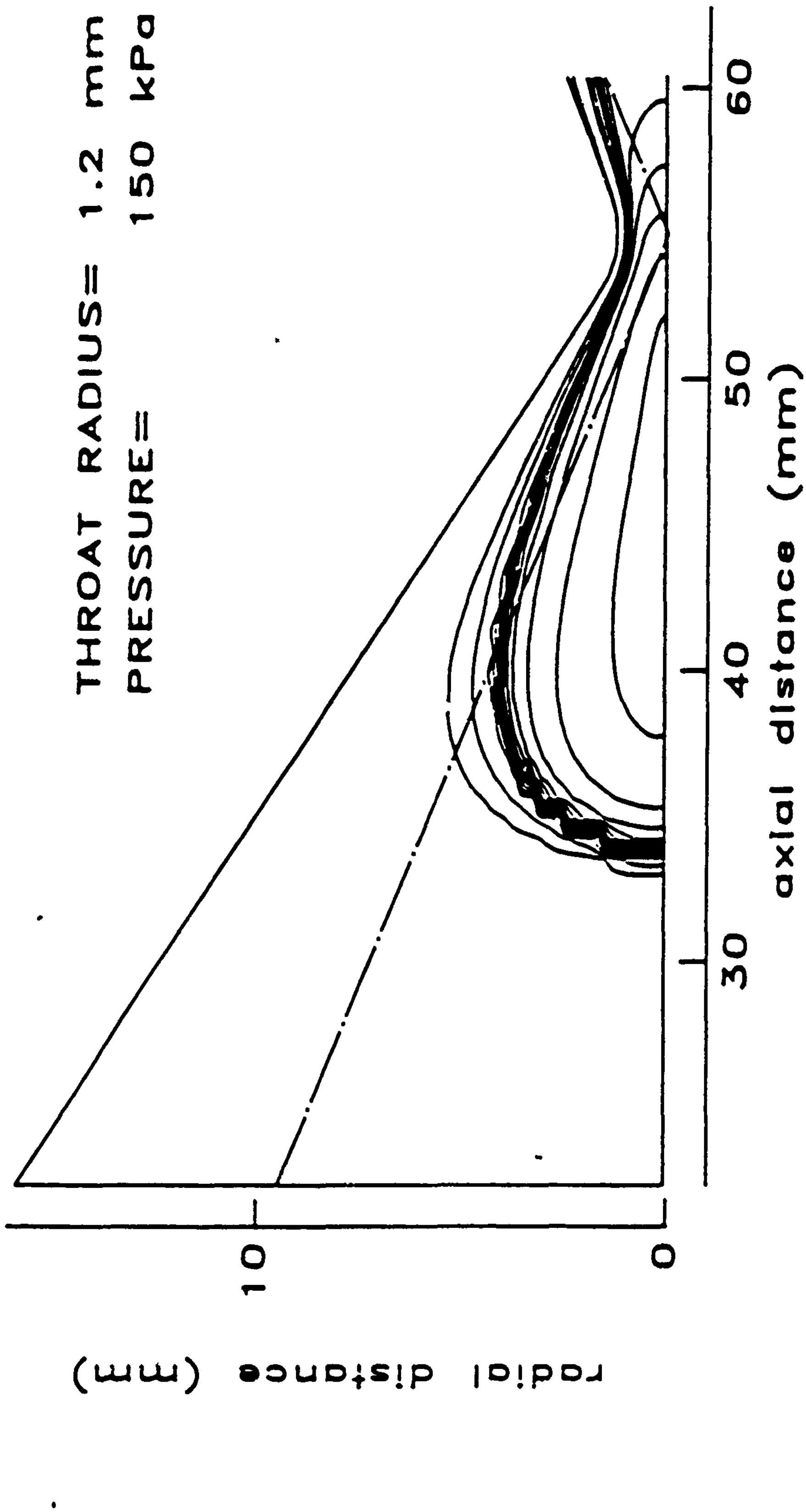

Cold Hydrogen
Hot Hydrogen
Laser Beam
Isp = 1500 secs
Focusing Lens
Hydrogen Plasma 15,000 K
IL-0361

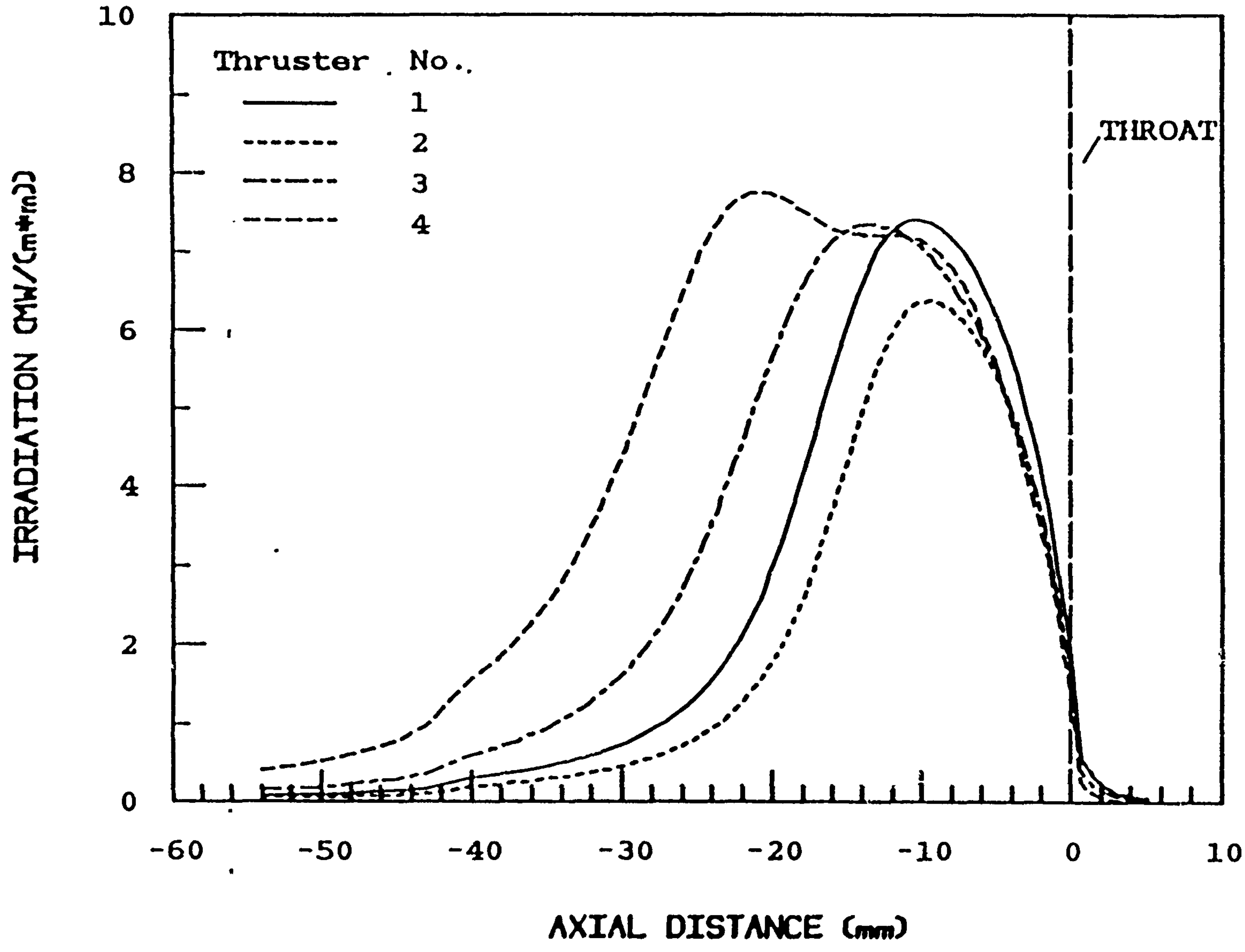


$R_c = 4 \cdot R_t$

IL-0362


THROAT RADIUS= 12mm
radial distance (mm)
20
10
0
10
20


THROAT RADIUS= 1.2 mm
PRESSURE= 150 kPa
axial distance (mm)
radial distance (mm)
30
40
50
60
0
10



Thruster No.
1
2
3
4
THROAT
IRRADIATION (MW/(m*m))
AXIAL DISTANCE (mm)
10
8
6
4
2
0
-60
-50
-40
-30
-20
-10
0
10

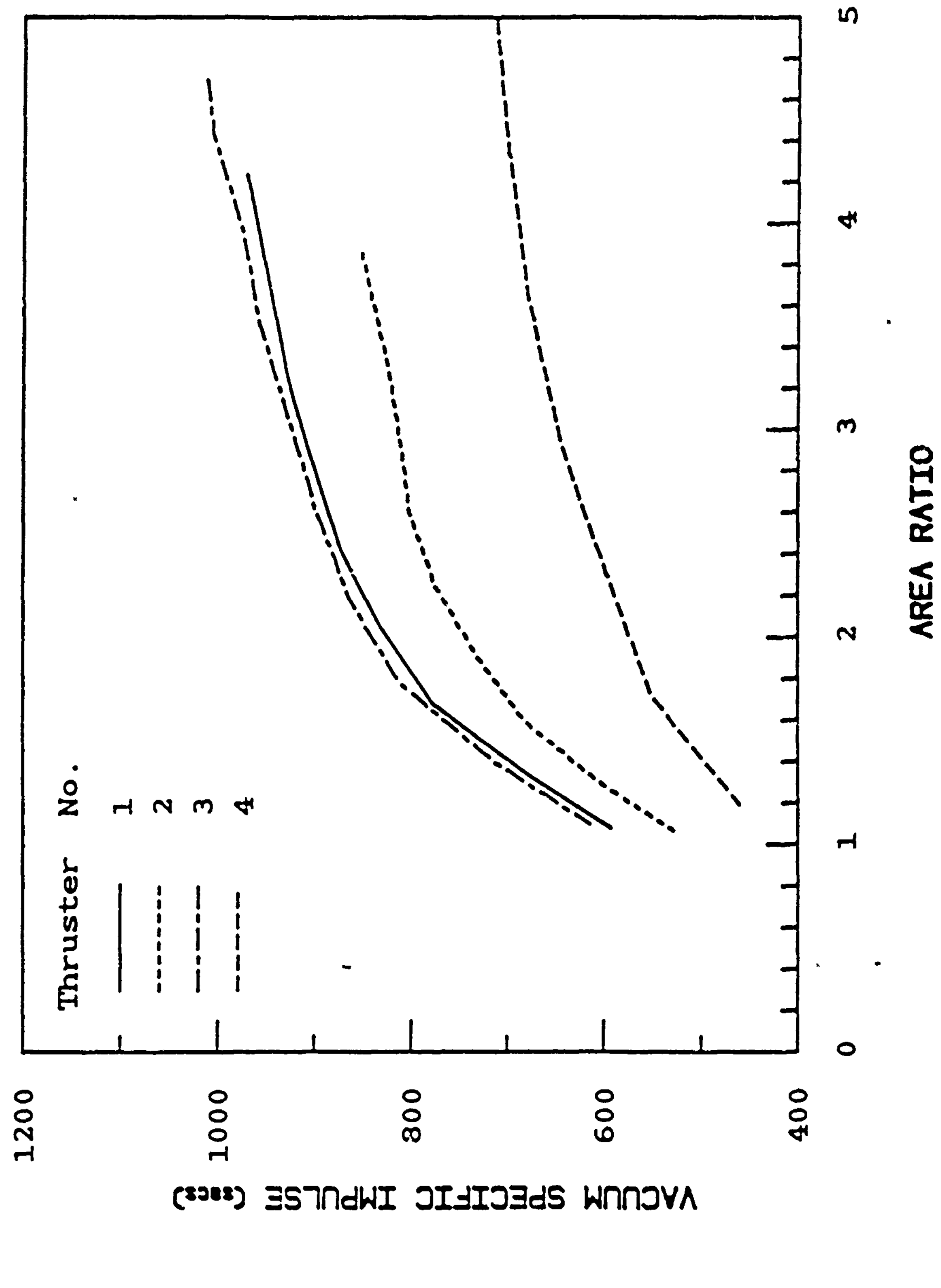

Thruster No.
1
2
3
4
VACUUM SPECIFIC IMPULSE (secs)
1200
1000
800
600
400
AREA RATIO
0
1
2
3
4
5

TABLE I.
Test Conditions

ROCKET NO.	1	2	3	4
Throat Radius (mm)	1.2	1.3	1.1	0.8
Inlet Pressure (kPa)	150	150	150	300

CG-0[illegible]31

TABLE II.
Performance of the Tested Rockets

ROCKET NO.	1	2	3	4
Transmitted Laser Power (kW)	4.9	5.7	4.2	0.8
Total Irradiation on Thruster (kW)	7.1	5.1	11.0	19.6
Mass Flow Rate (mg / sec)	90	118	73	121
Vacuum Specific Impulse* (sec)	960	859	980	686
Thrust* (N)	0.85	0.99	0.70	0.80

CG-0692

* at expansion area ratio of 4

TABLE III.
Expected Hydrogen Temperature vs. the Recovery Efficiency of Irradiation on Thruster

EFFICIENCY \ ROCKET NO.	1*	2*	3*	4**
100 %	2810 K	2390 K	3310 K	3430 K
50 %	2290 K	1420 K	2830 K	2950 K
25 %	1295 K	700 K	2220 K	2350 K

CG-0693

* at 150 kPa
** at 300 kPa

Conclusions

- Computer code based on an adequate physical model has been developed and verified
- Understanding of the LSP behavior has been greatly improved using the developed code
- Rocket thrusters supported by a 30 kW laser have been designed
  - Expected ISP approximately 1500 secs
  - Heat loading on thrusters comparable to chemical rockets

GL-0921

Suggested Future Research

- More sophisticated plasma radiative heat transfer model is needed
- Refraction and diffraction of laser beam through plasma should be considered
- Model for turbulence and LSP interaction should be proposed
- CFD Code should be extended to time-dependent, three-dimensional flows
- Current numerical algorithm should be improved to achieve better numerical accuracy

GL-0922

TURBULENT CONVECTIVE AND RADIATIVE TRANSPORT IN ADVANCED PROPULSION ENVIRONMENTS*

Robert A. Beddini
University of Illinois at Urbana-Champaign

BACKGROUND

While conventional chemical rockets provide large thrust levels at relatively low specific impulse, and electric propulsion systems provide low thrust levels at very high specific impulse, electrodeless plasma heated thrusters (implemented by various means) are capable of bridging this gap. These systems utilize large, controllable energy addition at moderate pressures to produce temperatures of the order 10^4 K. Concepts such as laser heated thrusters[1] and microwave heated thrusters[2] employ such controlled and directable energy addition to achieve a desired plasma zone (Figures 1,2). The plasma is then mixed with the outer flow and expanded through a nozzle. Of particular interest in such flows are turbulent convective and radiative heat fluxes, which distribute the deposited energy, and their effects on the system enclosure for chamber cooling requirements and evaluation of system efficiency. In systems utilizing laser sustained plasmas it is important to simulate high-power optical interactions with flowing gases in order to investigate the high energy/flow coupling as well as plasma parameters affecting system performance (i.e., plasma size, efficiency of absorption/ reradiation, peak temperature, etc.)

Research efforts under grant AFOSR 86-0319 have focused on the analysis of radiative and gas dynamic interactions in beamed-energy propulsion chamber environments. Specific topics have included the development of turbulence , incident radiative transport and reradiative transport. The following is a brief summary of the methodology being employed.

<u>Incident (laser) radiation:</u> A new transport equation for incident radiation was developed under this effort. Whereas prior analyses utilize ray-tracing techniques for the incident radiation, the new equation is of divergence form, and permits a strongly coupled solution with the hydrodynamic equations using contemporary finite volume techniques.

<u>Plasma and chamber wall reradiation:</u> The P1 (first-order spherical harmonics) method is being utilized. Initial work has solved the coupled one-dimensional (radial) radiative heat flux equation employing a gray gas absorption coefficient.

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* Abstract of presentation at the AFOSR Laser and Microwave Electrothermal Propulsion Workshop, University of Illinois at Urbana-Champaign, February 8-10, 1988.

Numerical solution method: A flux-split, non-factored, implicit finite volume method has been implemented for the time-accurate solution of the axisymmetric Navier-Stokes equations and coupled incident radiation field.

Turbulence: Initial results have been obtained with an established second-order turbulence closure model. In recent work, a more detailed description of turbulence is being examined.

EXAMPLE RESULTS FROM THE PRESENT EFFORT

A flow with specified energy addition (intended to simulate a TEM discharge in a microwave thruster), has been analyzed for both argon and hydrogen propellants. Flows with coolant injection through a porous chamber wall were also calculated.

The example case presented in Figures 3a-d, is the non-injected flow of argon through a constant area duct (R = .05848m) with inlet temperature and pressure of 2700 K and 1 atm respectively. Energy addition to the flow is 50 kW and mass flow is 0.028585 kg/s. Figure 3a shows the temperature field for this flow, indicating a peak temperature of approximately 10,000 K slightly downstream of the region of peak energy addition. Figure 3b shows the axial velocity field; the inlet centerline velocity is 23.2 m/s and the flow is accelerated and diverted towards the wall region by the strong heat addition. The centerline exit velocity is approximately 38 m/s. Figure 3c shows the turbulence intensity field for the flow (normalized by the local axial velocity on the centerline), where it can be seen that initial turbulence decays and is no longer supported in the high temperature, low Reynolds number flow in the central region. Near the wall region, however, the turbulence begins to grow in an annular region just off the chamber surface, reaching approximately 6% at an axial distance downstream of 10 radii. In Figure 3d the radial radiative heat flux is shown. The peak radiative flux delivered to the wall is approximately 800,000 W/m^2, and the overall peak radiative flux occurs near the core region with a value of 1.4 MW/m^2.

A comparison of radiative and convective surface heat fluxes as a function of axial distance is shown in Figure 4 for case involving: (1) argon, (2) argon with injection through the chamber wall (transpiration cooling), (3) hydrogen (non-injected), and (4) hydrogen injected. All cases have the same approximate chamber "thrust", and the dominance of radiative transfer in the region of energy addition is clearly seen. The strong effect of radiative transfer is further demonstrated in Figure 5 which compares the centerline temperature distribution for case one with the radiative solution participating and non-participating.

Although turbulence fails to be supported due to low Reynolds numbers encountered in the high temperature regions, it can be produced transitionally in the cooling layer near the surface. The exit Reynolds numbers based on chamber diameter, axial mass flux, and centerline viscosity are on the order of 10^3 for the

conditions considered. However, Reynolds numbers near the edge of the plasma are on the order of 20,000 based on local flow properties; such values would usually be expected to provide at least moderate levels of turbulence.

With respect to laser-gas dynamic interactions, the incident intensity field calculated with the third order finite difference method for a 60 radial by 80 horizontal point grid is shown in figure 6 for a non-absorbing medium. For this grid, approximately 6 radial and three axial points are retained within the 1 cm diameter of focal volume. Maximum relative errors of approximately 5% are obtained in this region when compared with an exact solution developed for this case.

Figure 7 shows a comparison of the analytic and computational solutions for relative intensity as a function of axial distance along the centerline and at radial position off the centerline. The calculated centerline solution and peak intensity are in excellent agreement for this case, but computational errors with coarser grids or much smaller relative focal spot sizes increase proportionately. An example calculated temperature field is shown in Figure 8 for a laser-gasdynamic interaction. The peak temperature is approximately 9300 K (utilizing an artificial absorption coefficient), and the relatively sharp upstream rise indicates a near plasma wave formation for these conditions. Note also that a secondary increase in temperature is obtained downstream of the focus in the diverging region of the beam.

RESEARCH RECOMMENDATIONS

It would appear that the analytical results of three efforts and the experimental results of two efforts presented at this AFOSR workshop have, *de facto*, provided at least one major consensus of opinion: radiative transport issues in the chamber (and, perhaps nozzle) environments of laser and microwave propulsion systems are important. Further research is required to address radiative-flowfield interactions which include losses from the plasma and transfer to and from the nozzle walls. Radiative transfer to the chamber surface does not provide a major impediment from a systems point of view, however, since cooling techniques have been suggested by more than one investigator which have the potential to accommodate significant chamber surface fluxes.

The present results indicate that for systems of a size (or Reynolds number) larger than traditional laboratory configurations, turbulence could form in the annular coolant layer adjacent to the chamber surface, and hence introduces the problem of a transitional or retransitional flow. A more adequate analytical representation of turbulence development should be pursued, possibly by formulating a large-eddy simulation appropriate for these types of aerophysical environments. The effects of turbulence are not necessarily adverse, since the enhanced mixing that results could reduce peak chamber temperatures at a faster rate, thereby reducing radiative transfer.

Microwave–heated plasma propulsion appears promising as an onboard energy conversion/propulsion system since power-to-beam conversion efficiencies are substantially higher than present laser efficiencies. Additionally, the plasma region supported by the various microwave discharge modes is far greater in volume than the focal region of single plasma laser discharges, and thus radiative losses could be lower due to lower peak chamber temperatures (at given chamber pressures). However, the plasma frequency limit noted by Keefer produces an undesirably low limit on microwave discharge temperatures and thermal efficiencies, as indicated by Micci's literature review. Further research is therefore required, and it may prove beneficial to implement concepts developed in the microwave-heated fusion community, where the problem has been well addressed for a different environment.

Finally, the question of pulsed laser propulsion introduces several new research issues. These include nonequilibrium propellant energy states, chamber aeroacoustic interactions, and electromagnetic effects (the Schwartz-Hora magnetic pulse is an example). The breadth of these actual and potential issues will require the attention of several research investigators, with commensurate benefits toward the advancement of space propulsion.

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3. Beddini, R. A., Owano, T. G. and Kuo, S. -L., "Analysis of Gas Dynamic Interactions with Intense Optical Beams," AIAA paper no. 87-1455, AIAA 19th Fluid Dynamics, Plasma Dynamics and Laser Conference, Honolulu, Hawaii, June 1987.

4. Beddini, R. A. and Owano, T. G. "Analysis of Turbulent Convective and Radiative Heat Transfer in High Temperature Rocket Chamber Flows," AIAA paper no. 87-1770.

TURBULENT CONVECTIVE AND RADIATIVE ENERGY TRANSFER IN HIGH TEMPERATURE SYSTEMS

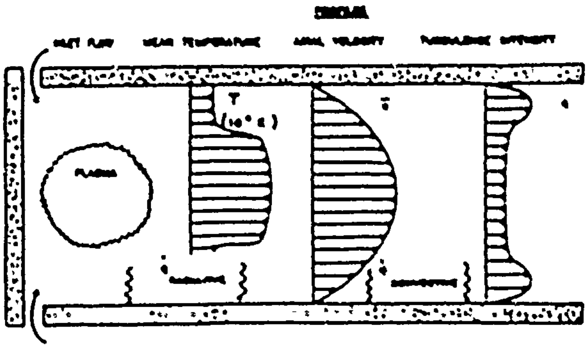


Figure 1

Figure 1: Schematic diagram of the thrust chamber of a generic high temperature plasma heated thruster, showing radiative heat fluxes to the chamber walls due to the high temperature (> 10,000 K) core, as well as convective heat fluxes due to near wall turbulence.

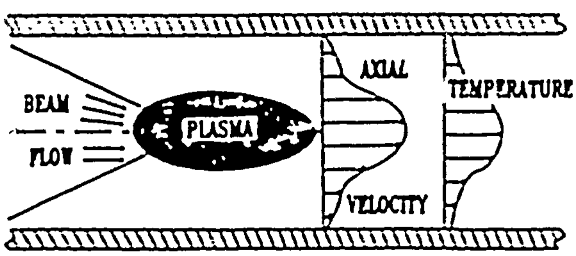
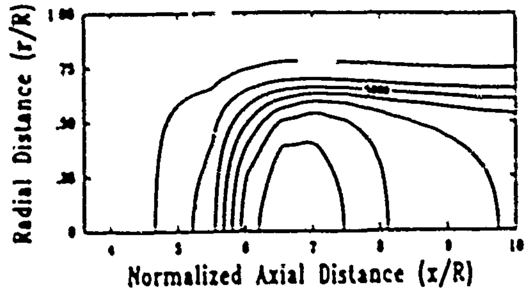
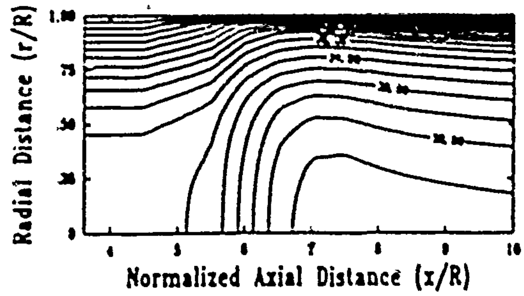


Figure 2

Figure 2: Schematic of a laser sustained plasma in a ducted flow along with representative temperature and velocity distributions.

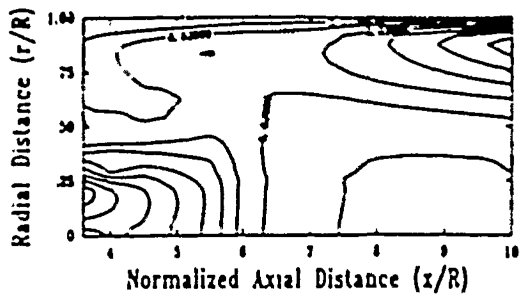


a)

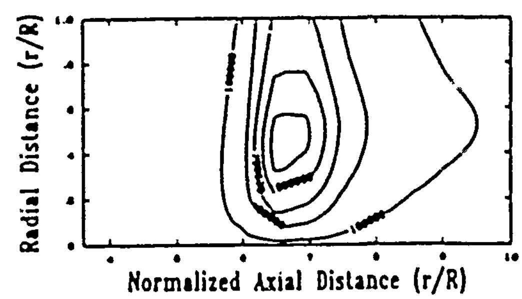


b)

Figure 3: a) Temperature field for a non-injected flow of argon gas through a constant area duct (R = 0.3048 m). Inlet temperature and pressure are 2700 K and 1 atm respectively. Energy addition to the flow is 30 kW and mass flow is 0.032363 kg/s. Centerline inlet velocity is 23.2 m/s. Contour increment is 10^3 K.
b) Corresponding axial velocity field.



c)



d)

Figure 3: c) Turbulence intensity field (normalized by the local axial velocity on the centerline) for the flow described previously.
d) Corresponding radial radiative heat flux field. Maximum surface heat flux levels approach 100,000 W/m^2; contour increment is 5×10^3 W/m^2.

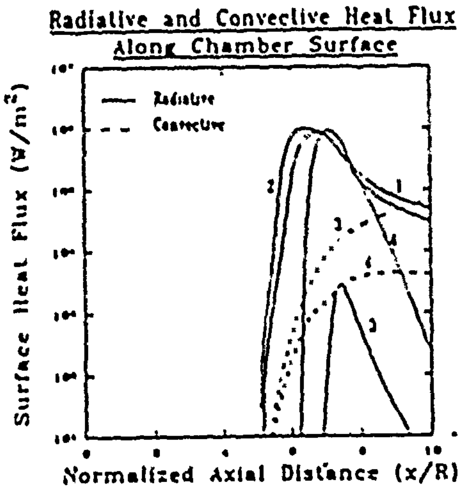


Figure 4

Figure 4: [illegible]

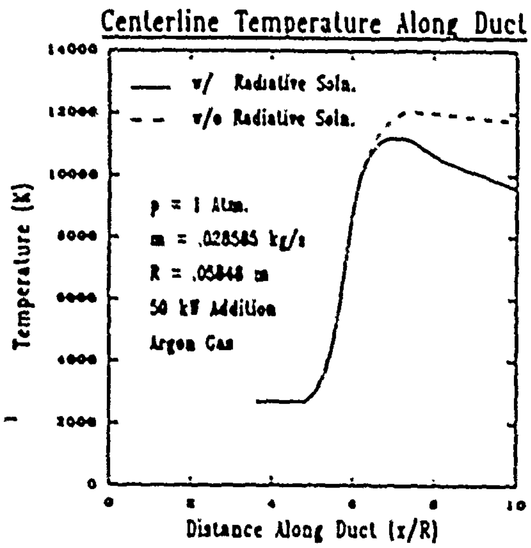


Figure 5

Figure 5: [illegible]

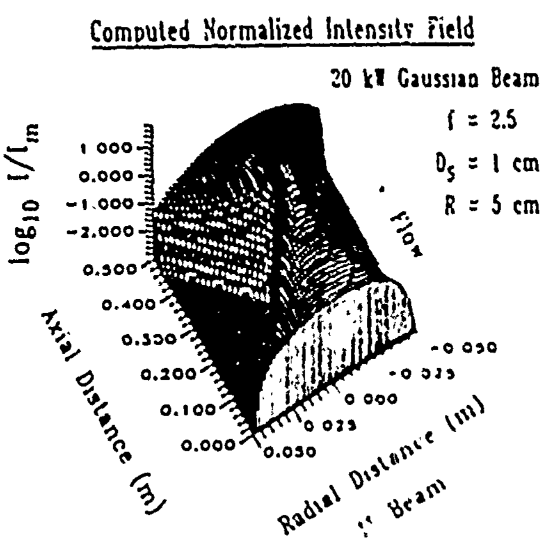


Figure 6

Figure 6: [illegible]

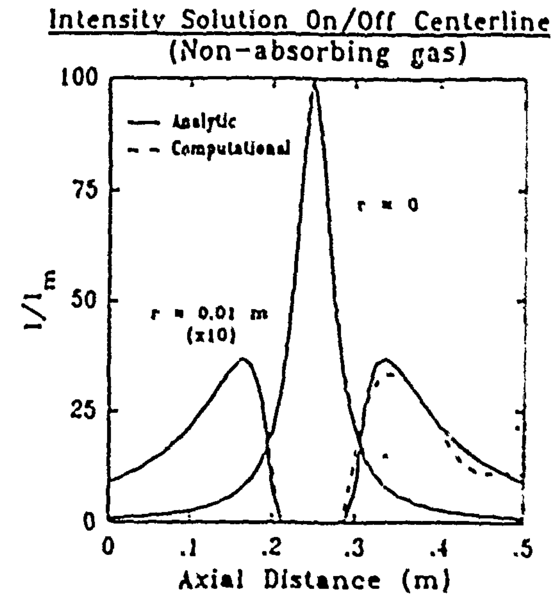


Figure 7

Figure 7: [illegible]

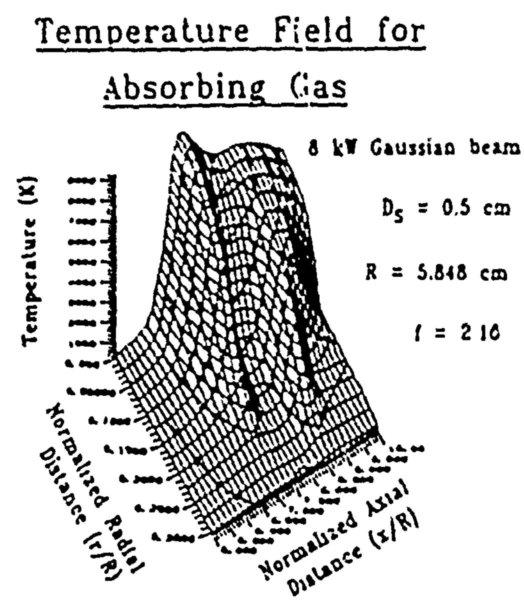


Figure 8

Figure 8: [illegible]

RESEARCH ACTIVITIES/NEEDS/PLANS IN THERMAL SPACE PROPULSION

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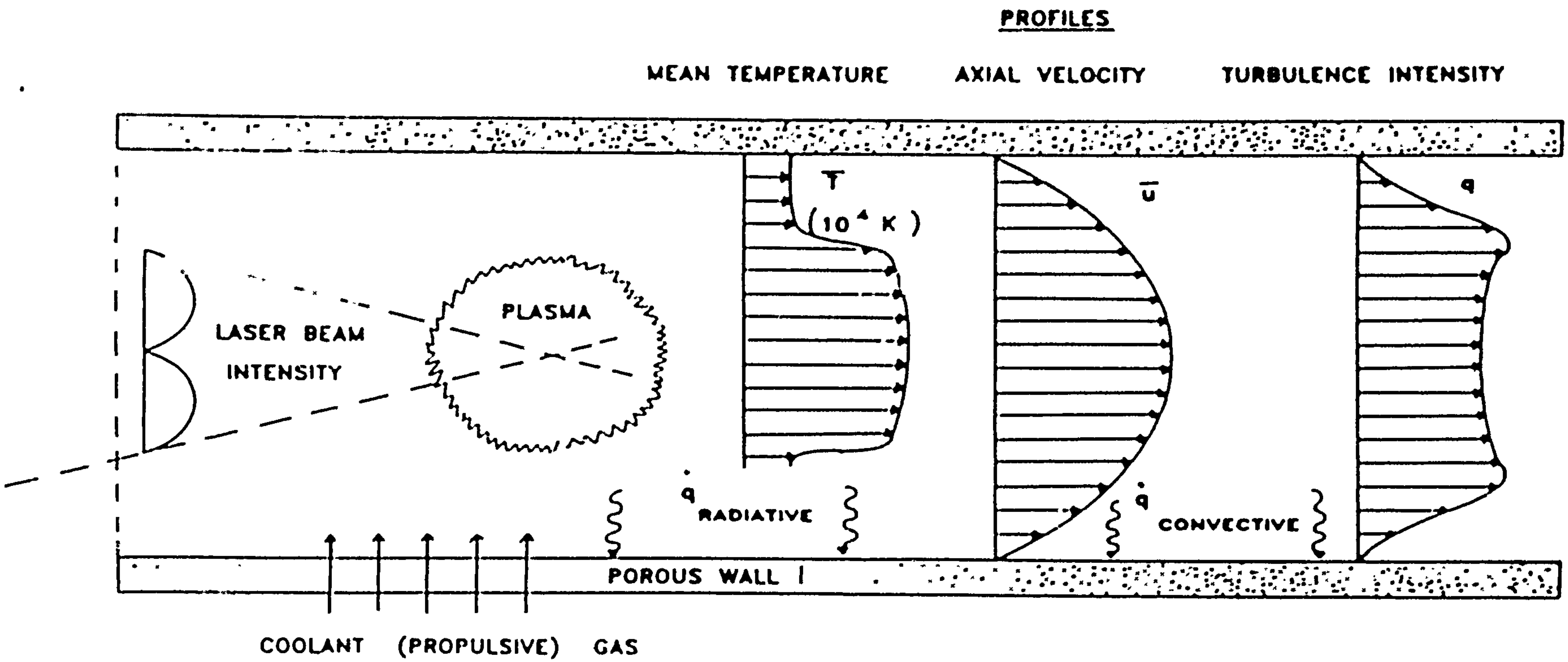
Presentation at the
AFOSR Laser and Microwave Rocket
Propulsion Research Meeting

University of Illinois
February 8–10, 1988

Research Supported by AFOSR (AFSC)
Under Grant 86–0319

TURBULENT CONVECTIVE AND RADIATIVE ENERGY TRANSFER IN LASER PROPULSION CHAMBERS



RESEARCH ISSUES

- THE HIGH TEMPERATURE PLASMA MUST MIX-OUT BEFORE THE NOZZLE IF HIGH EFFICIENCIES ARE TO BE REALIZED.
- LONG FOCAL LENGTH BEAMS AND HIGH VELOCITIES INCREASE ABSORPTION EFFICIENCY.

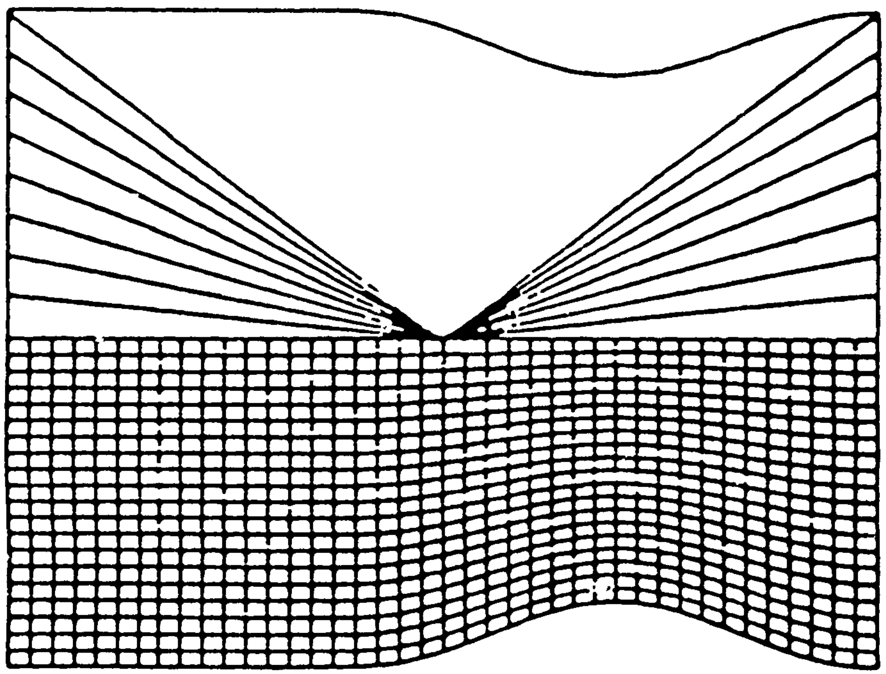
  => HIGH L/D CHAMBERS
- HIGH VELOCITIES AND MODERATE PRESSURES => TRANSITIONAL/TURBULENT FLOW WITH ATTENDANT INCREASE IN CONVECTIVE HEAT TRANSFER.
- WHAT ARE THE RELATIVE MAGNITUDES OF $\dot{q}_{radiative}$ AND $\dot{q}_{convective}$?
- CAN TURBULENCE AND TURBULENT HEAT TRANSFER BE SUFFICIENTLY SUPPRESSED BY LARGE INJECTION RATES THROUGH THE POROUS CHAMBER WALL?

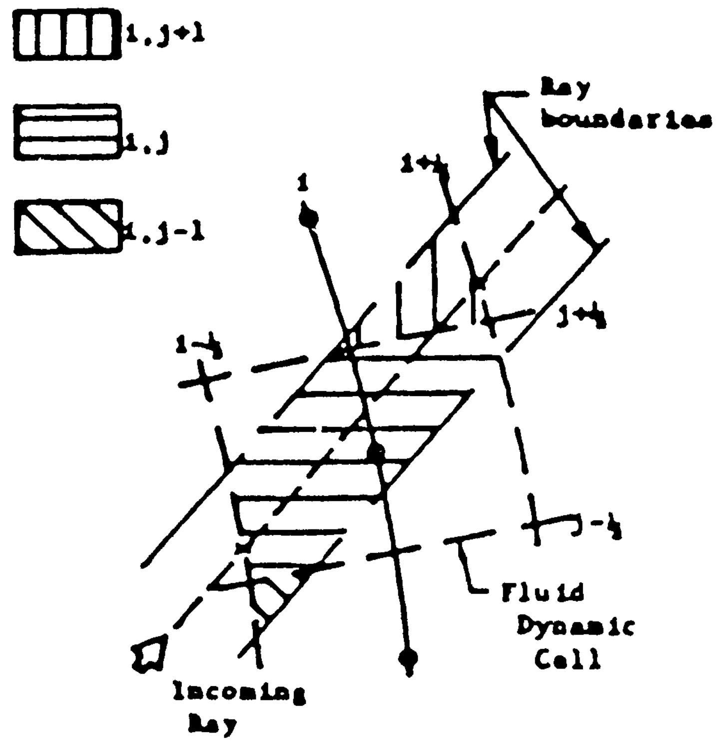
CONVENTIONAL LINE-OF-SIGHT APPROACH

- THE RADIATIVE FIELD IS GEOMETRICALLY DISCRETIZED ALONG SEVERAL RAYS.
- THE INTENSITY ALONG THE jth RAY IS CALCULATED FROM

$$\frac{dI_j}{ds} = -\alpha I_j$$

- THE INTENSITY WITHIN A FLUID CELL IS CALCULATED FROM "RAY OVERLAP" AND FLUX DIRECTION ACCOUNTING ACROSS THE NON-ALIGNED FLUID CELL.





BEAM CONTINUUM APPROACH

- THE BASIC EQUATION FOR RADIATIVE TRANSFER IN AN ABSORBING, NONSCATTERING MEDIUM IS

$$\nabla \cdot (\vec{k}J) = -\alpha_\nu J$$

WHERE J IS THE ENERGY/UNIT (AREA, WAVENUMBER, SOLID ANGLE).

- FOR IDEAL LASER PROPAGATION ALONG A <u>RAY</u> WITH LOCAL DIRECTION $\vec{\ell}(x)$,

$$J(t, \vec{x}, \vec{k}, \nu) = J'(\vec{x}, t)\ \delta(\vec{k} \cdot \vec{\ell} - 1)\ \delta(\nu - \nu_o)$$

- DEFINING THE RADIATIVE FLUX (INTENSITY) AS

$$I = \iint J d\nu d\Omega$$

THE TRANSFER EQUATION IS

$$\nabla \cdot (\vec{\ell} I) = -\alpha I$$

ATTRIBUTES OF THE BEAM CONTINUUM APPROACH

- ADVANTAGES
  - FULL COUPLING TO FLUID ENERGY EQUATION WITH STRONG CONSERVATION POSSIBLE, I.E.,

$$\nabla \cdot (\vec{\ell} I) = -\alpha I$$

$$\frac{\partial(\rho e)}{\partial t} + \nabla \cdot (\rho \vec{u} h + \vec{\ell} I) = -\nabla \cdot (\vec{q}_c + \vec{u}\tau)$$

  - INTENSITY SOLVED CONSISTENTLY WITH SAME FLUID SOLUTION TECHNIQUE AND SAME (ADAPTIVE) GRID.

- DISADVANTAGES
  - UPWIND DIFFERENCING ERRORS DIFFUSE BEAM SHARPNESS, ALTHOUGH PEAK INTENSITIES ARE WELL PREDICTED.
  - MULTIPLY-REFLECTED OR HIGHLY ASTIGMATIC BEAMS REQUIRE SOLUTION OF SEVERAL INTENSITY EQUATIONS.

ANALYTIC SOLUTION FOR INCIDENT RADIATION

- LOCAL DIRECTION COSINES APPROXIMATED BY CONFOCAL HYPERBOLAE

$$\ell_r = \frac{r\,\xi}{[r^2\xi^2 + (b^2 + \xi^2)^2]^{1/2}}$$

$$\ell_x = \frac{(b^2 + \xi^2)}{[r^2\xi^2 + (b^2 + \xi^2)^2]^{1/2}}$$

- QUASI-GAUSSIAN INITIAL PROFILE

$$I = I_m(1 - r^2/a_o^2)^2$$

- ANALYTIC SOLUTION IS:

$$I = I_m \frac{\left(1 - \frac{d^2}{\gamma^2 a_o^2}\right)^2 d^{3/2}\,[(2+2\gamma^2)\zeta - 2b^2]^{1/2}}{[(2+2\gamma^2)d - 2b^2]^{1/2}\,\zeta}$$

where $\gamma = \dfrac{[b^2 + (x - x_f)^2]^{1/2}}{r}$ and $d = b^2 + x_f^2$

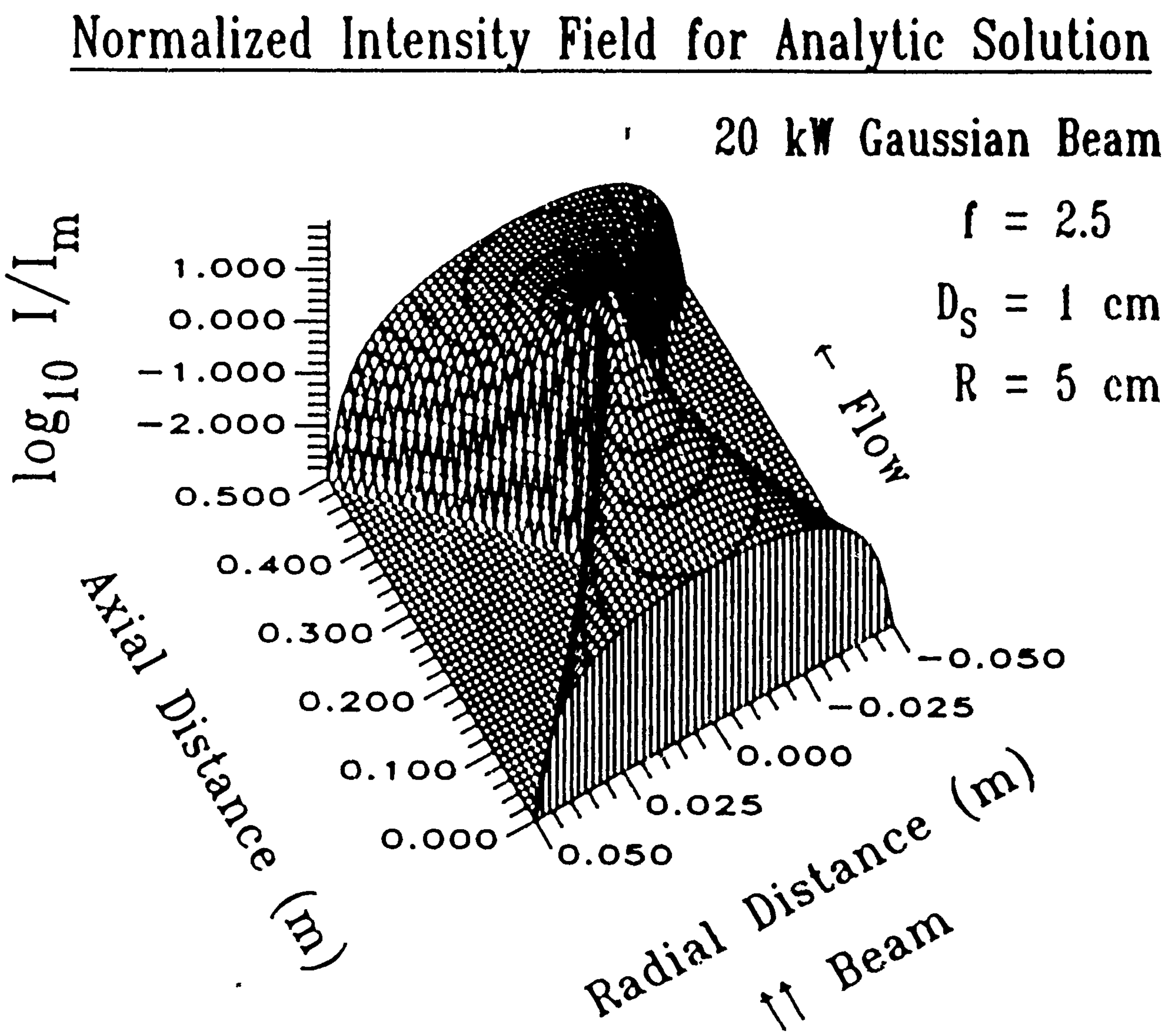
The solution along the centerline is $I = I_m\zeta_o/\zeta$.

<u>FINAL EQUATIONS</u>

$$\frac{\partial Q}{\partial t} + \frac{\partial F}{\partial \zeta} + \frac{\partial G}{\partial \eta} + H = \frac{1}{Re}\left(\frac{\partial F_1}{\partial \zeta} + \frac{\partial G_1}{\partial \eta} + H_1\right)$$

where

$$Q = J^{-1}\begin{bmatrix} r\rho \\ r\rho u \\ r\rho v \\ rE \\ rI/c_o \\ \dfrac{3r\beta q_x}{c_o} \\ \dfrac{3r\beta q_r}{c_o} \end{bmatrix} \qquad F = J^{-1}\begin{bmatrix} \rho U \\ \rho u U + \zeta_x p \\ \rho v U + \zeta_r p \\ U(E+p) - \zeta_t p \\ r\ell_x I \\ 0 \\ 0 \end{bmatrix} \qquad H = J^{-1}\begin{bmatrix} 0 \\ 0 \\ -p \\ -r\alpha I \\ r\alpha I \\ -r\left(\dfrac{\partial^2 q_x}{\partial x^2} \quad \dfrac{\partial^2 q_x}{\partial r^2}\right) + \dots \\ -r\left(\dfrac{\partial^2 q_r}{\partial x^2} + \dfrac{\partial^2 q_r}{\partial r^2}\right) + \dots \end{bmatrix}$$



Normalized Intensity Field for Analytic Solution
20 kW Gaussian Beam
f = 2.5
D_S = 1 cm
R = 5 cm
← Flow
$\log_{10} I/I_m$
1.000
0.000
−1.000
−2.000
0.500
0.400
0.300
0.200
0.100
0.000
Axial Distance (m)
−0.050
−0.025
0.000
0.025
0.050
Radial Distance (m)
↑↑ Beam

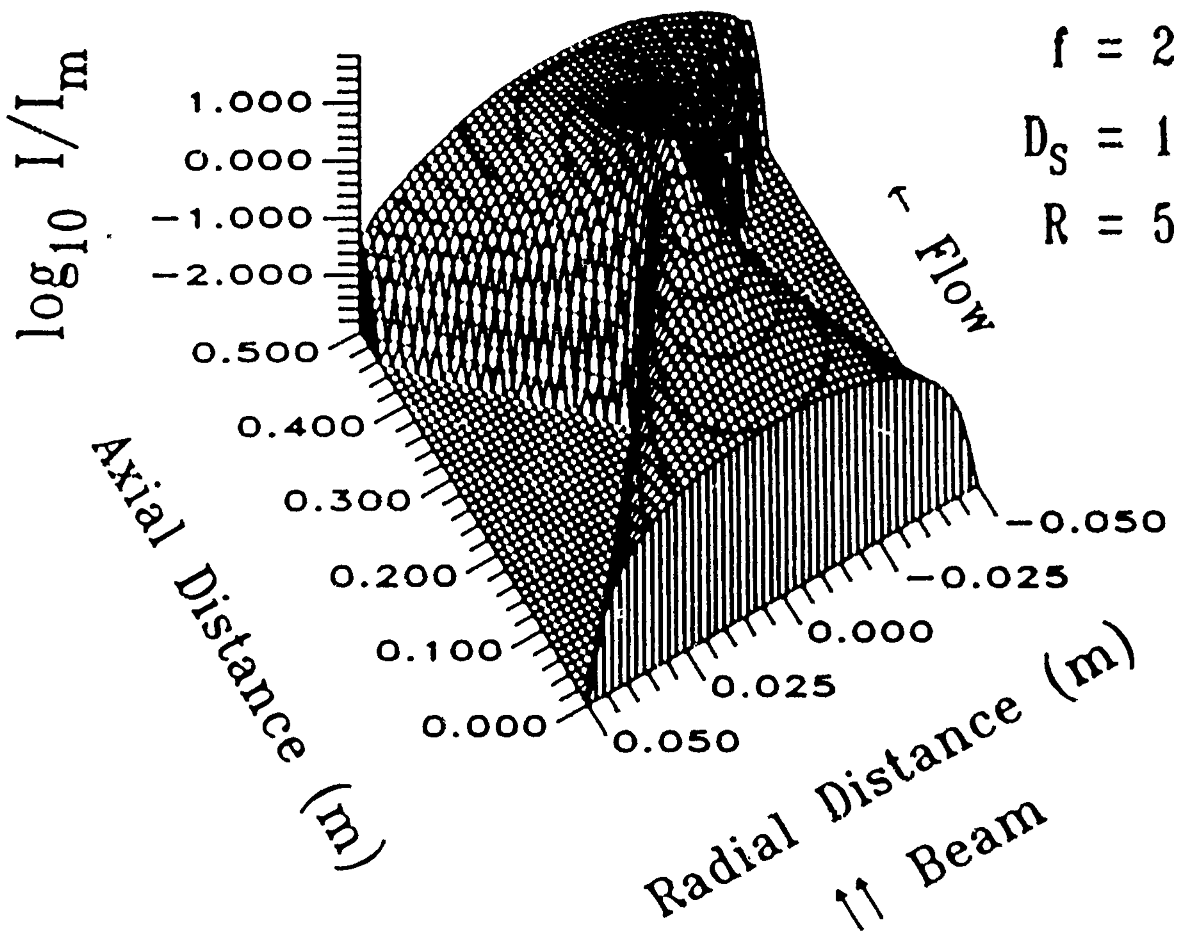
Computed Normalized Intensity Field

20 kW Gaussian Beam

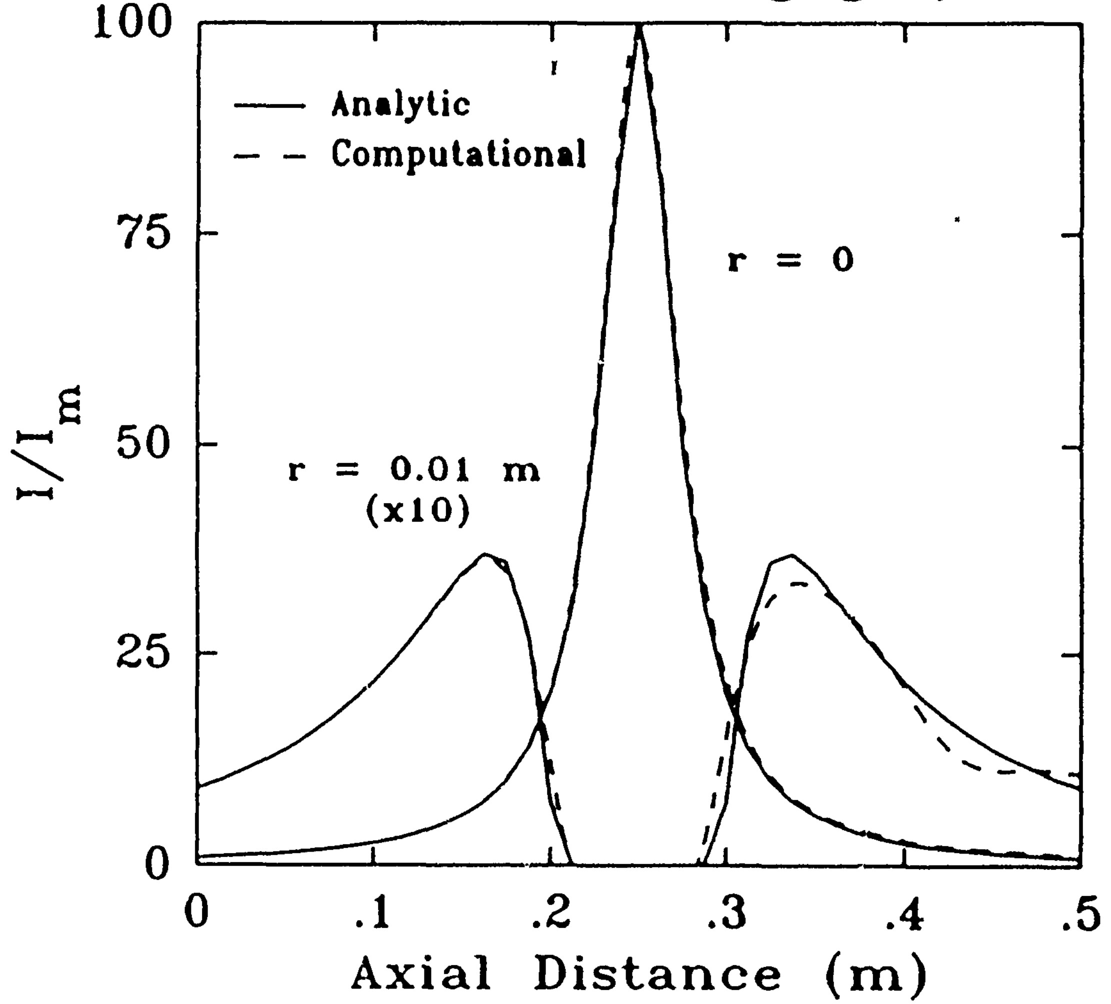
$f = 2.5$

$D_S = 1$ cm

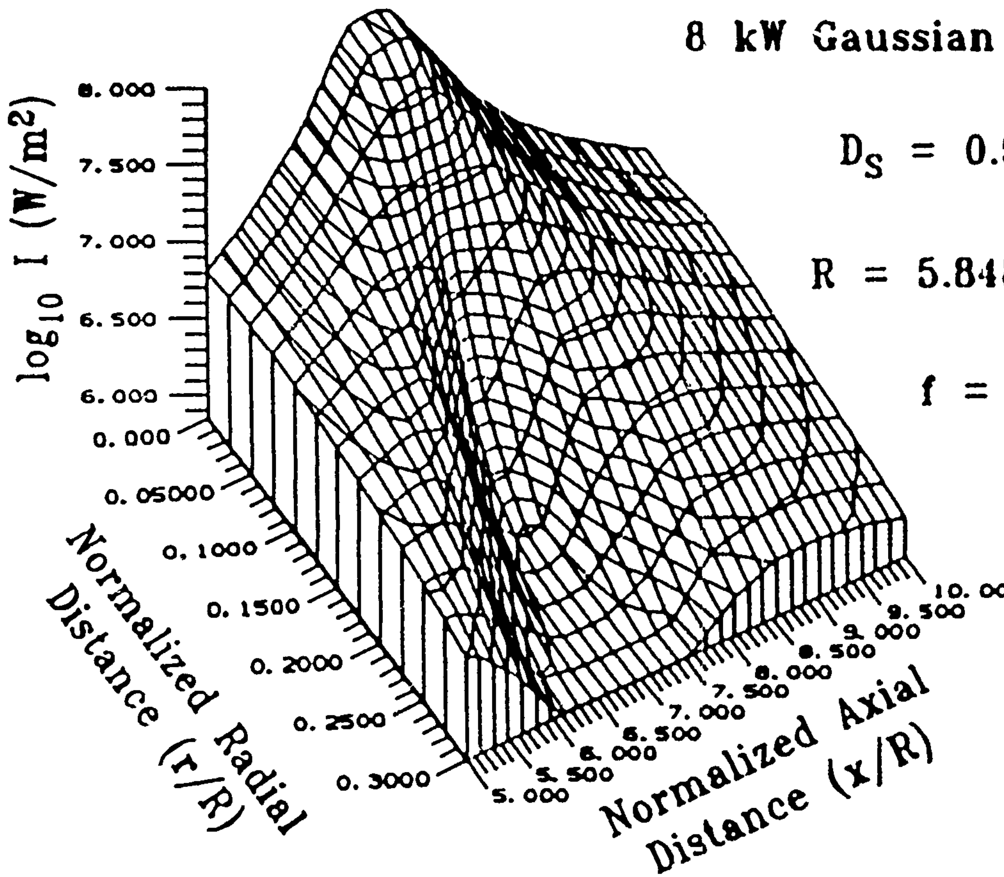
$R = 5$ cm



Intensity Solution On/Off Centerline
(Non-absorbing gas)



Laser Intensity Field for Absorbing Gas



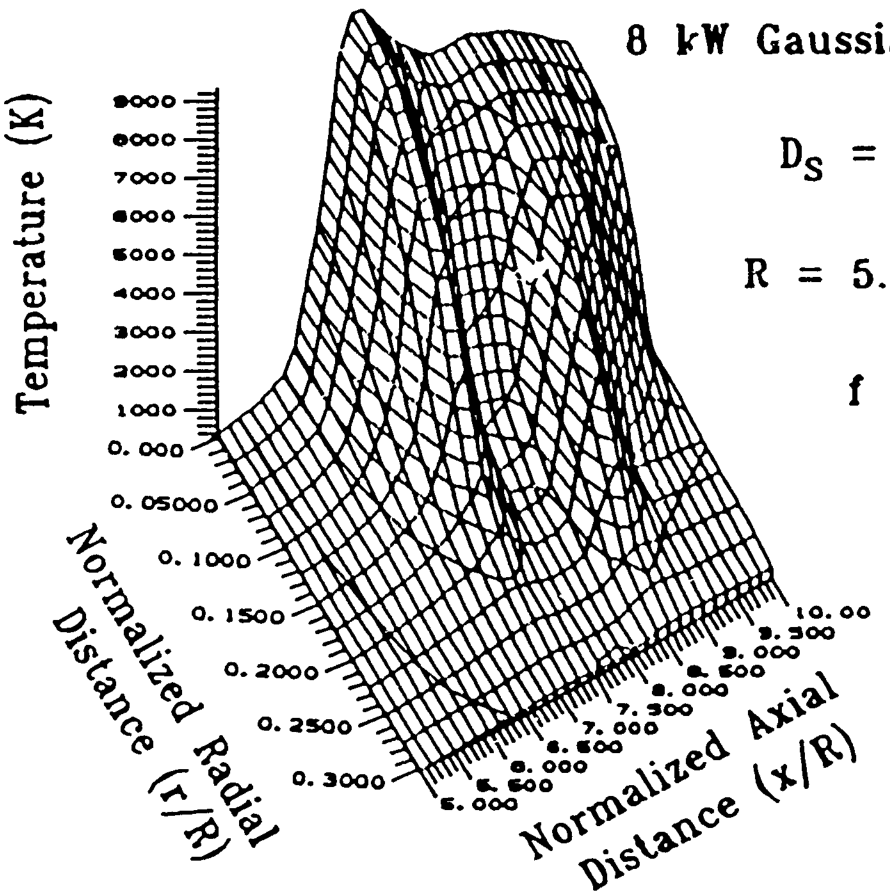
8 kW Gaussian beam

$D_S = 0.5$ cm

$R = 5.848$ cm

$f = 2.16$

Temperature Field for Absorbing Gas



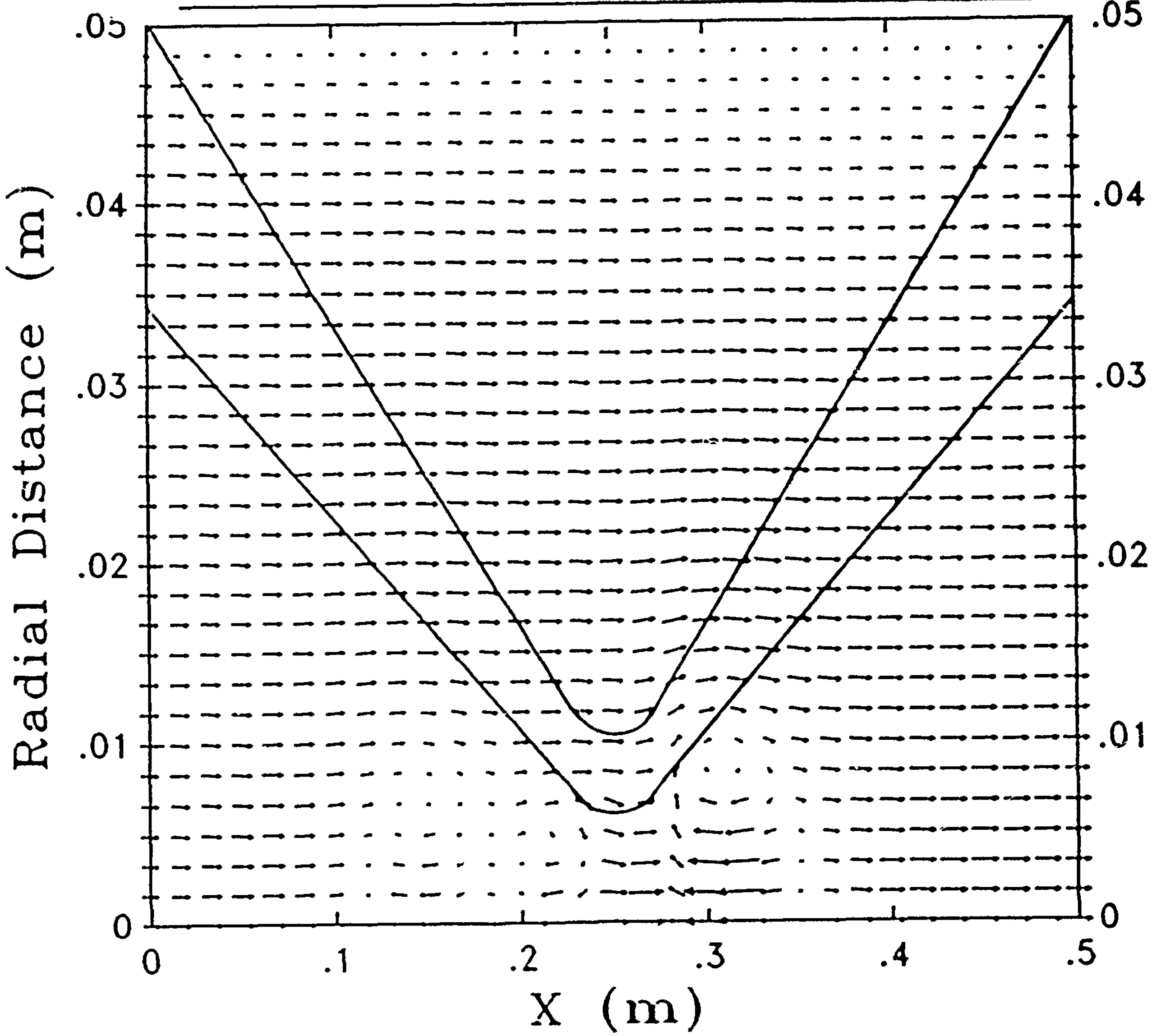
8 kW Gaussian beam

$D_S = 0.5$ cm

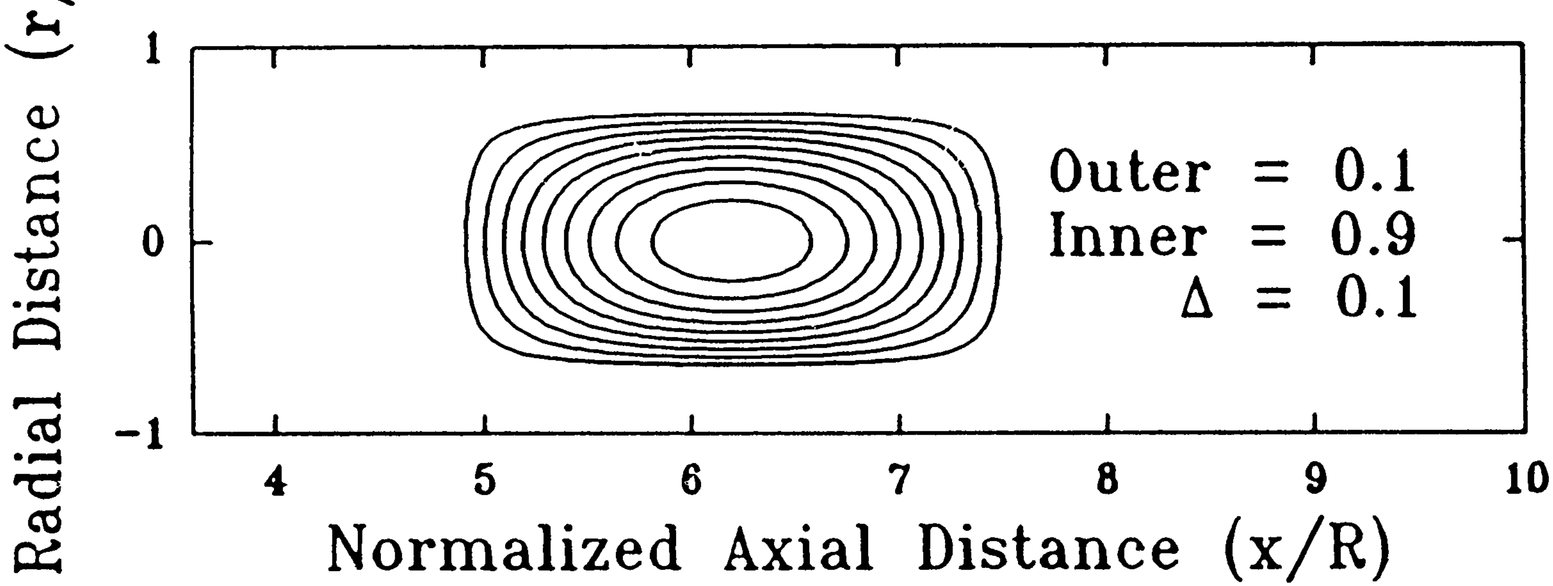
$R = 5.848$ cm

$f = 2.16$

Starting Vortex Formed by Laser Interaction with Argon Flow

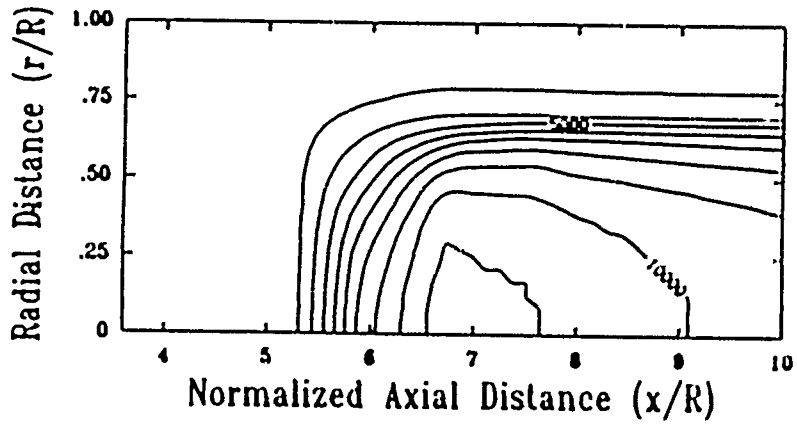


Energy Addition Field

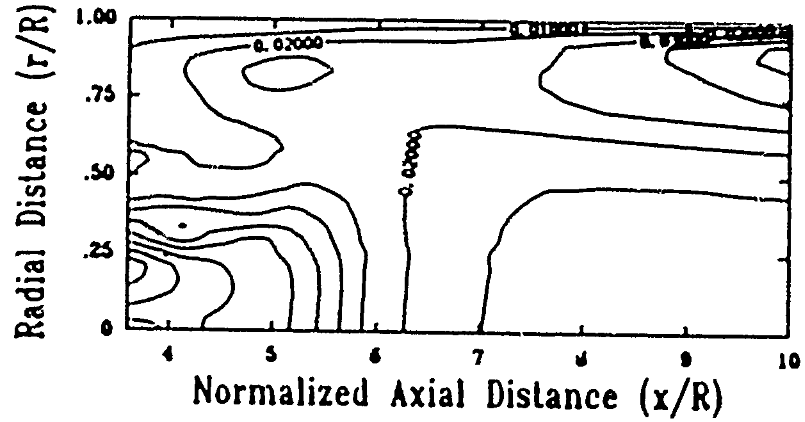


Argon Gas - 50 kW Addition

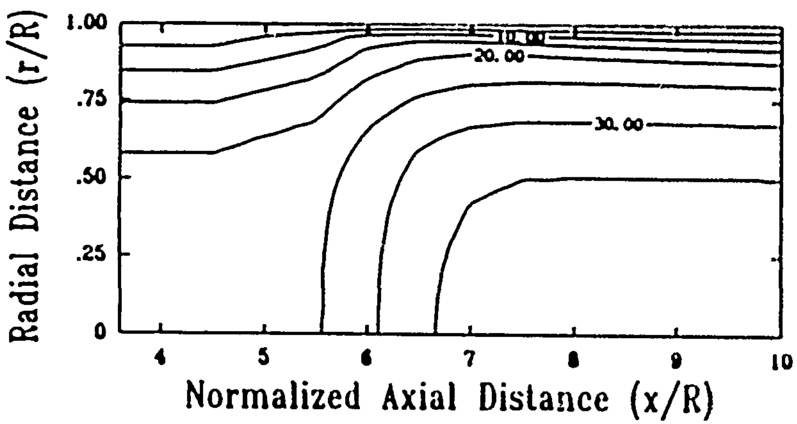
Temperature Field



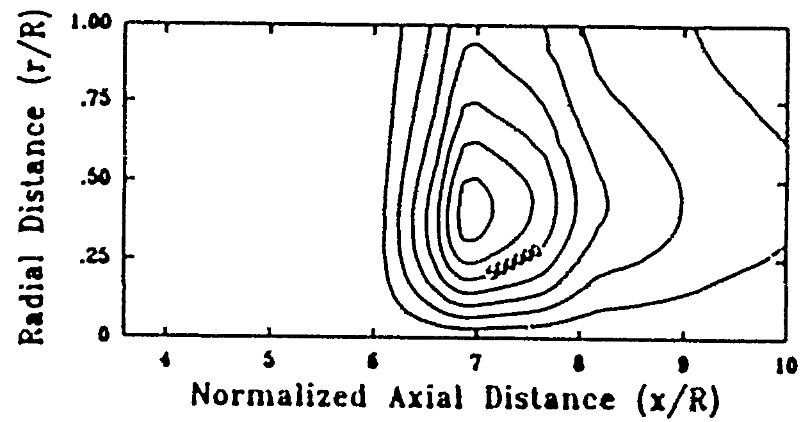
Turbulence Intensity Field



Axial Velocity Field (m/s)

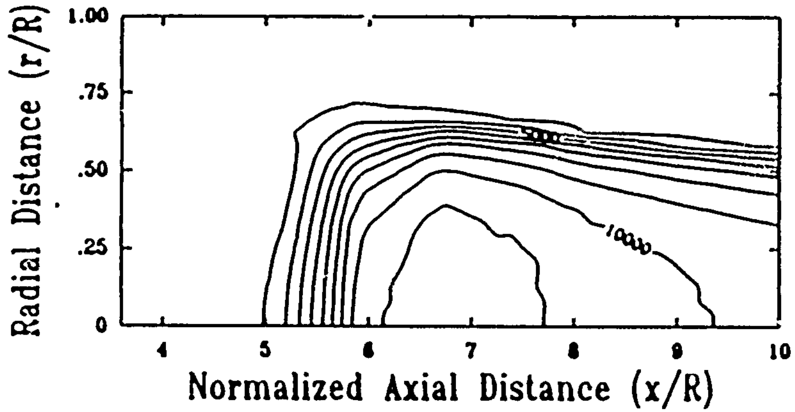


Radial Radiative Heat Flux

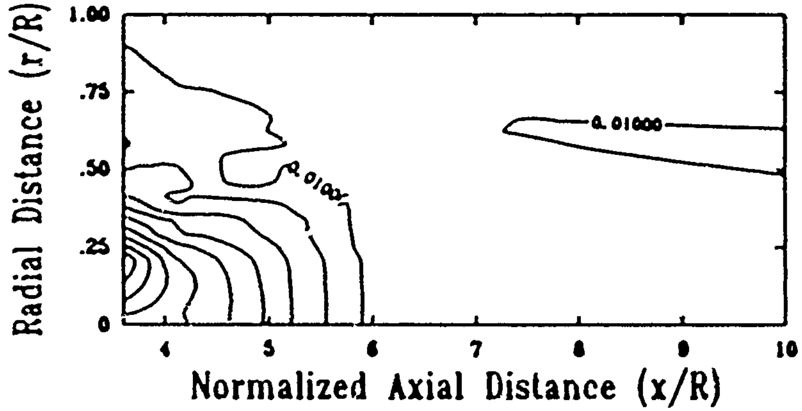


Argon Gas - Injected Flow - 50 kW Addition

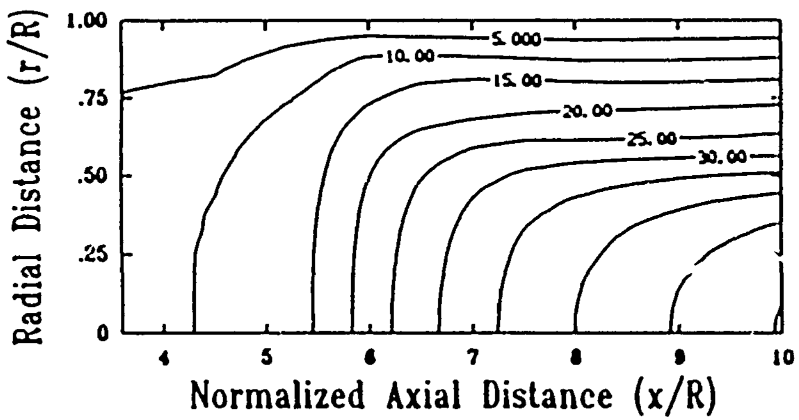
Temperature Field



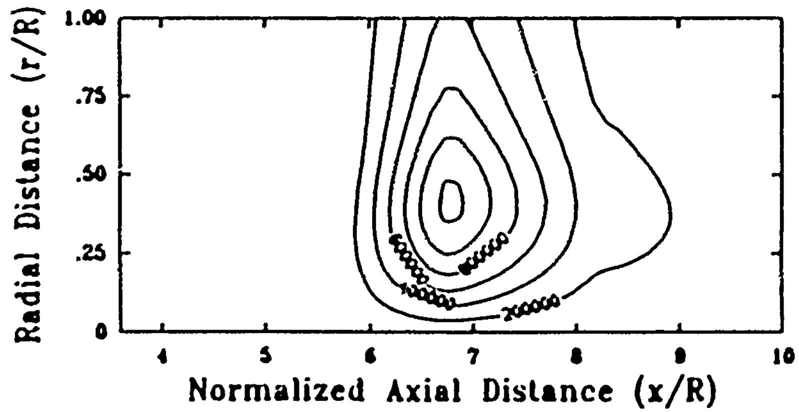
Turbulence Intensity Field



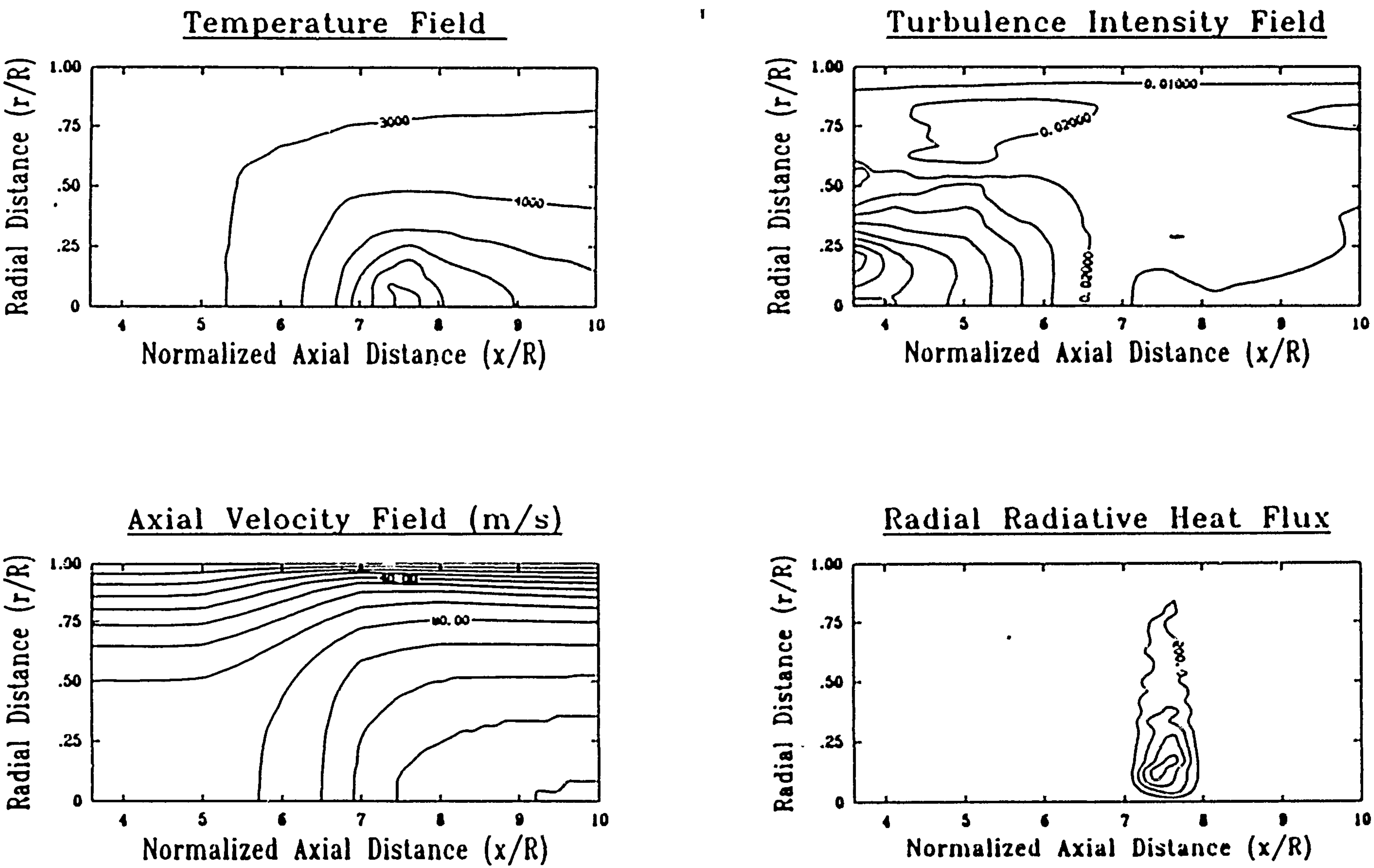
Axial Velocity Field (m/s)



Radial Radiative Heat Flux

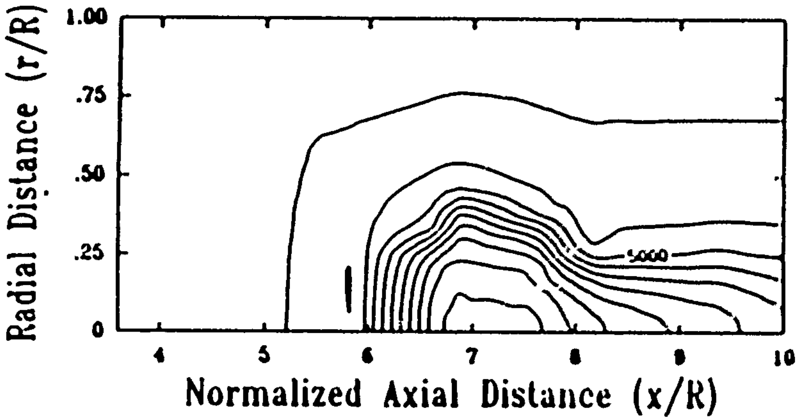


Hydrogen Gas - 300 kW Addition

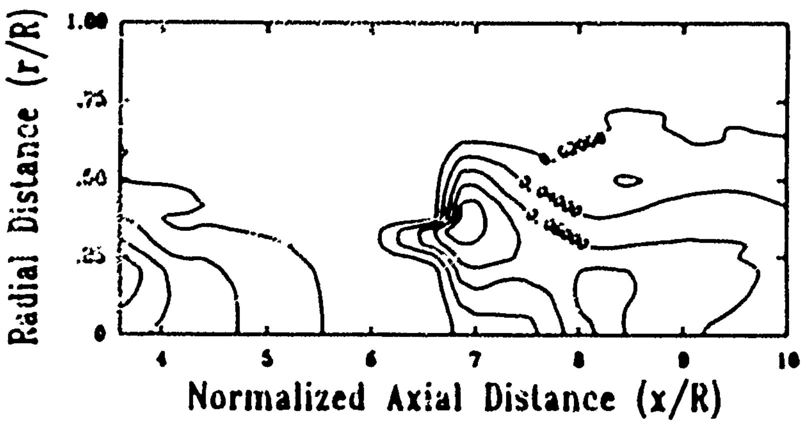


Hydrogen Gas - Injected Flow - 300 kW Addition

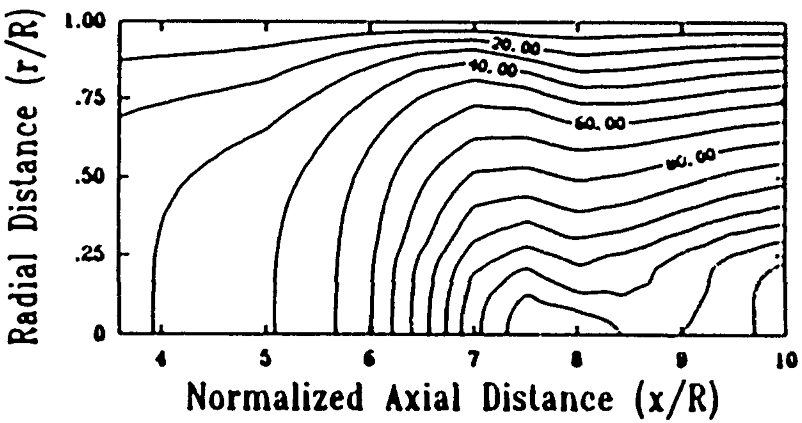
Temperature Field



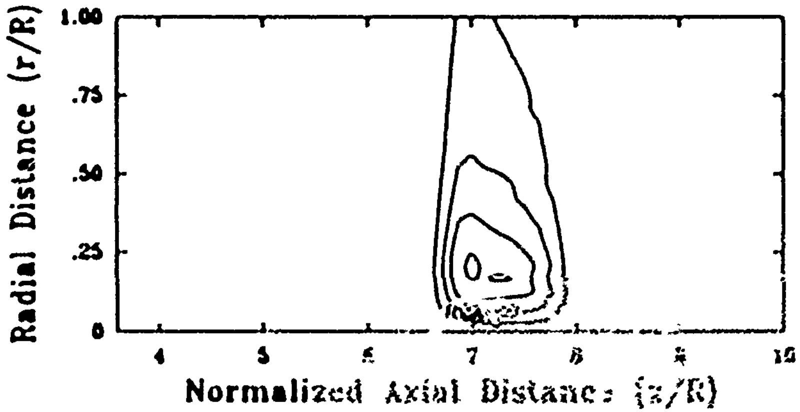
Turbulence Intensity Field



Axial Velocity Field (m/s)



Radial Radiative Heat Flux



CONCLUSIONS

- A NEW METHOD FOR THE ANALYSIS OF LASER SUPPORTED PLASMAS WITHOUT RAY TRACING HAS BEEN DEVELOPED. POTENTIAL ADVANTAGES:
  - FLUID AND RADIATIVE TRANSPORT SOLVED BY THE SAME NUMERICAL SOLUTION TECHNIQUE ON THE SAME GRID
  - UNSTEADY BEAM/PLASMA INTERACTIONS ON IRREGULAR DOMAINS
- AN ANALYTIC SOLUTION IS OBTAINED FOR NON ABSORBING MEDIA
- FLUX-SPLIT, FINITE VOLUME METHOD FOR RADIATIVE AND GAS-DYNAMIC SOLUTION:
  - ACCURATE AGREEMENT WITH ANALYTIC SOLUTION FOR BEAM PROPAGATION
  - INSTABILITIES EXPERIENCED DURING PLASMA IGNITION → PRESENT RESULTS OBTAINED USING PARABOLIC FLUID DYNAMICS
- PRESENT PHYSICAL RESULTS (E.G., LOW RATE OF THERMAL MIXING, HIGH PLASMA RADIATION LOSS) ARE IN QUALITATIVE AGREEMENT WITH PRIOR EXPERIMENTAL/THEORETICAL RESULTS
- FURTHER WORK IS REQUIRED ON BEAM PROPAGATION
  - INCLUDE REFRACTION EFFECTS, ACCOUNT FOR THERMAL BLOOMING
  - MULTI-PHOTON ABSORPTION AT HIGHER FREQUENCIES

CONCLUSIONS

SPECIFIED ENERGY ADDITION TO CHAMBER FLOWS

- PREDOMINANT HEAT TRANSFER MECHANISM FOR LOW MACH NUMBER, HIGH TEMPERATURE (10,000 K) CHAMBER FLOW IS DUE TO RERADIATION.
- TURBULENCE IS PREDICTED TO DEVELOP AT LOW LEVELS IN AN ANNULAR REGION NEAR THE SURFACE, BUT THERMAL MIXING IS SUPPRESSED.
- RADIATIVE HEAT FLUX OF APPROXIMATELY 10^6 W/m^2 CAN BE EFFECTIVELY COOLED WITH MODERATE TRANSPIRATION VELOCITIES THROUGH THE CHAMBER SURFACE.

MODELLING AND COMPUTATIONAL RESEARCH NEEDS

- NEEDS GO WELL BEYOND 3-D CAPABILITY
- TIME ACCURACY NEEDED FOR LSD SHOCKS AND TO SIMULATE POTENTIAL INSTABILITIES
- SPATIAL ACCURACY NEEDED - FIRST ORDER UPWIND METHODS ARE TOO DIFFUSIVE
- PULSED LASER INTERACTIONS: ASSESS KINETICS EFFECTS AND E.M. EFFECTS FROM PLASMA VORTICES.
- FULLY COUPLED TREATMENT REQUIRED FOR FLOW RERADIATION (E.G., CHAMBER WALLS AT 3000K CAN RERADIATE A SUBSTANTIAL AMOUNT OF ENERGY).

AEROSPACE TECHNOLOGY DIRECTORATE

SPACE PROPULSION TECHNOLOGY DIVISION

NASA
Lewis Research Center

AFOSR LASER PROPULSION WORKSHOP

FEBRUARY 8–10, 1988

DAVE BYERS

NASA LEWIS RESEARCH CENTER

PROGRAM OBJECTIVE

DEFINE, EVALUATE, AND PROVIDE PROPULSION TECHNOLOGY FOR SPACECRAFT, LARGE SPACE SYSTEMS, AND VEHICLES

SPONSOR

- SDIO/IST

AGENT

- NASA LeRC

PROGRAM ELEMENT

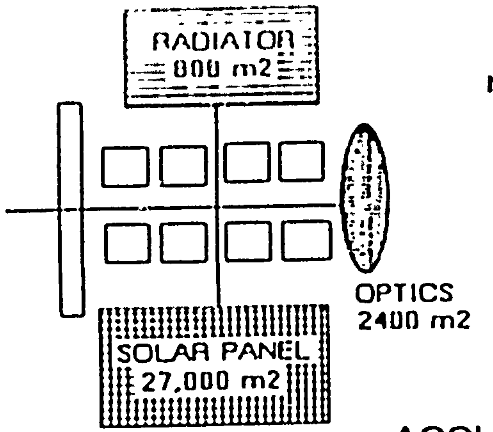
- SMALL BUSINESS INNOVATIVE RESEARCH
  - PROPULSION AND LOGISTICS –
- SCIENCE AND TECHNOLOGY
  - ELECTRIC PROPULSION –
- LOW THRUST PROPULSION

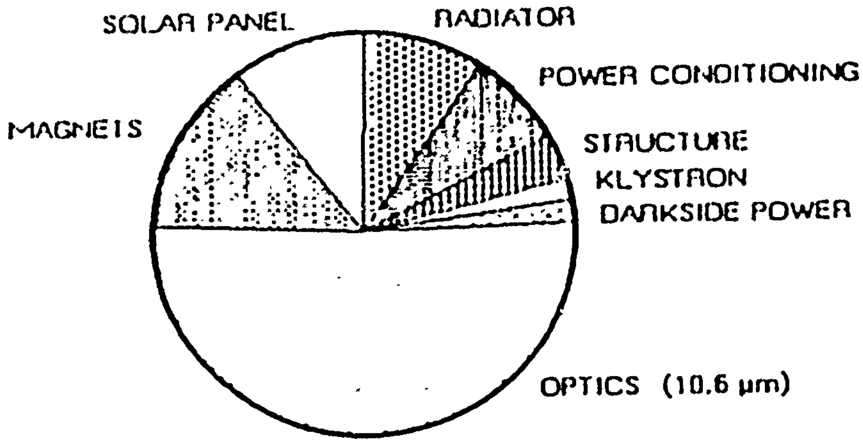
SPECIFIC OBJECTIVES

- O PROVIDE METHODOLOGY / TECHNICAL BASES REQUIRED FOR SYSTEM/MISSION EVALUATIONS OF LASER PROPULSION CONCEPTS
- O IDENTIFY AND QUANTIFY DRIVER/LIMITING ISSUES AND ASSOCIATED SCHEDULES
- O CONDUCT LASER PROPULSION SYSTEM DESIGNS TO
  - FLEX AND REFINE THE METHODOLOGIES
  - ESTABLISH BOUNDS ON SELECTED SYSTEM CHARACTERISTICS
  - DEFINE AREAS OF HIGH LEVERAGE/RISK
  - PROVIDE DIRECTON FOR LATER EFFORTS

FREE ELECTRON LASER (FEL)

POWER = 1 MW   MASS = 142,000 kg





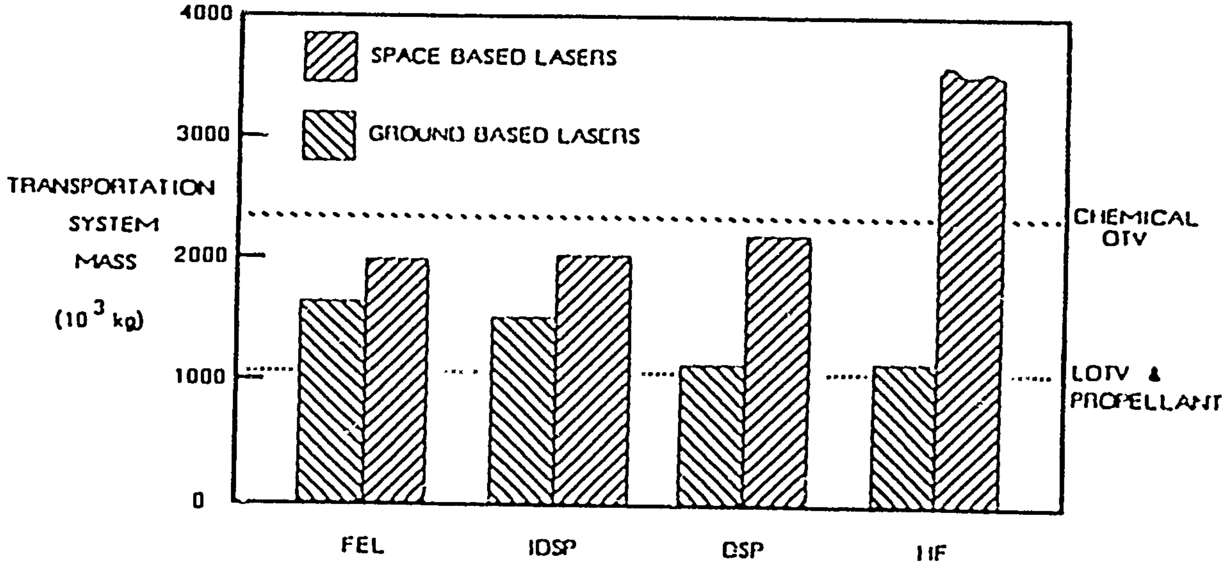
ASSUMPTIONS

ELECTRIC – TO – LASER EFFICIENCY = 40%
WAVELENGTH = 10.6 µm
ZERO LASANT FLUID RESUPPLY
MULTIPLE–PASS, CATALAC CONFIGURATION
POWER CONDITIONING = 11.25 kg/kW L

AEROSPACE TECHNOLOGY DIRECTORATE

SPACE PROPULSION TECHNOLOGY DIVISION

NASA
Lewis Research Center



SECTION B

LAWRENCE LIVERMORE NATIONAL LABORATORY

DOUBLE-PULSE LASER PROPULSION

DR JORDIN T. KARE

Why Laser Propulsion?

SDIO Laser Propulsion Program

- Cheap, flexible, high performance
  - All the hard parts stay on the ground
    - Laser
    - Optics
    - Guidance
  - 500-1500 s I_{sp} from a block of "ice"
- High volume launch to orbit – \$10 - 100/lb
  - One payload every 15 minutes
    - Payload set by laser size: 1-2 kg/MW from $\approx$ 25 MW up
    - Inherently pipelined, low overhead operation
    - Even entry system (25 MW, few \$100M) launches > 1000T/yr.
  - Launch to any orbit
    - LEO any inclination (even retrograde)
    - GEO transfer
    - Escape
- Deliver thrust (or power) anywhere in sight of laser
  - Plane changes – dither orbits to confuse tracking
  - Boost satellites to high orbit
    - Move large masses with multiple "burns" (100's of kg/MW)
    - GEO insertion with space mirror or reflector on vehicle
  - Orbital maintenance (drag make-up) – sustain very low orbits

TO KEEP IT SIMPLE

LETS KEEP EVERYTHING ON THE GROUND <u>EXCEPT</u>

PAYLOAD

PROPELLANT

AND

PHOTONS

<u>PERIOD</u>

THE FOUR P PRINCIPLE

SDIO Laser Propulsion Program

DOUBLE-PULSE LSD-WAVE* THRUST CYCLE

A) "Metering" pulse evaporates a thin layer of propellant

$\tau_1 = 2 - 5\ \mu s$

B) Gas expands to the desired density

$\tau_{1\text{-}2} = 0 - 5\ \mu s$

C) Main pulse passes through gas, forms plasma at surface

τ_{ign} = few ns

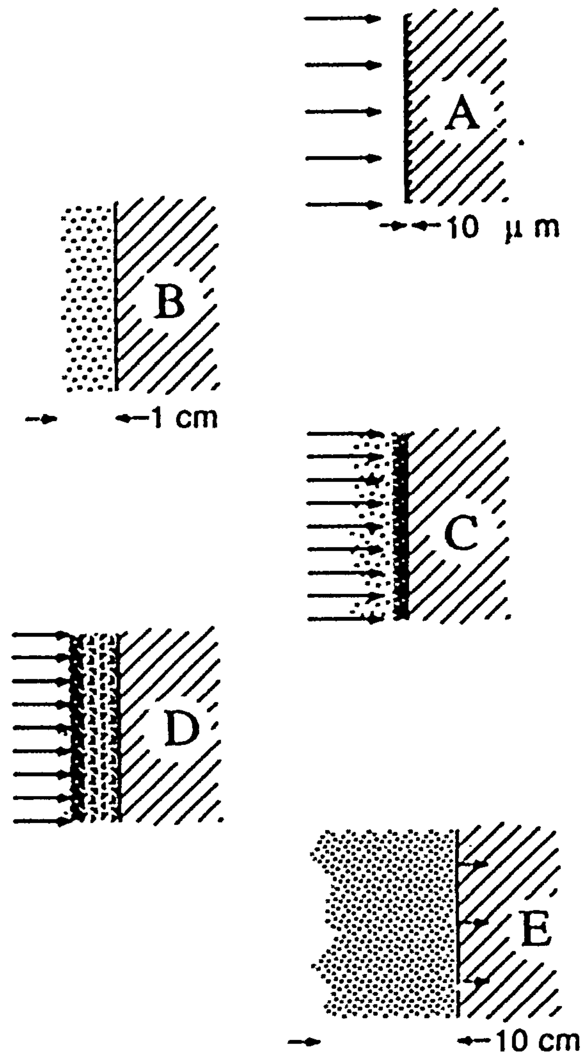
D) Plasma absorbs beam by inverse bremsstrahlung; absorbing layer (LSD wave) propagates through gas

$\tau_2 = 1\ \mu s$

E) Uniformly hot gas expands in 1-D, producing thrust

$\tau_{exp} = 3 - 10\ \mu s$

F) Exhaust dissipates; cycle repeats at 100 Hz - few kHz

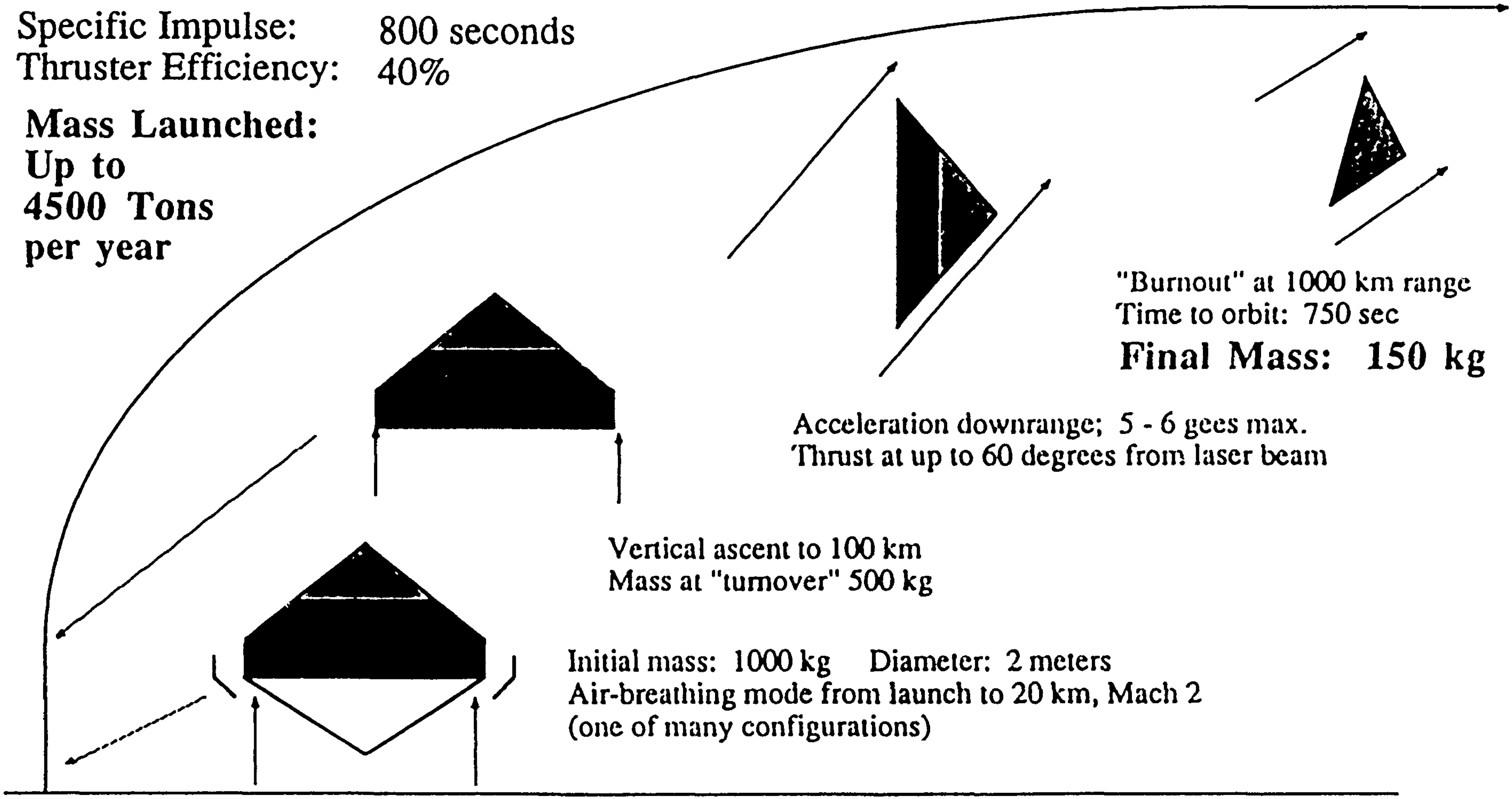


LASER PROPULSION SYSTEM: REFERENCE DESIGN

SDIO Laser Propulsion Program

Laser power:	100 MW	Telescope diameter: 10 Meters
Laser wavelength:	10 microns	
Specific Impulse:	800 seconds	
Thruster Efficiency:	40%	

Mass Launched:
Up to
4500 Tons
per year



MAJOR LASER PROPULSION ISSUES

- PHYSICS
  - Thruster
  - Atmospheric Propagation
- ENGINEERING
  - Laser
  - Beam Transport Optics
  - Beam Projector(s)
  - Adaptive Optics
  - Vehicle
  - Guidance and Control
- Launch
- Site
- Safety
- Environmental Effects

THRUSTER EFFICIENCY – The Key Issue

$$\eta_{thr} = 1/2\dot{M} < v_{exh} >^2 / P_{Laser}\eta_{trans}$$

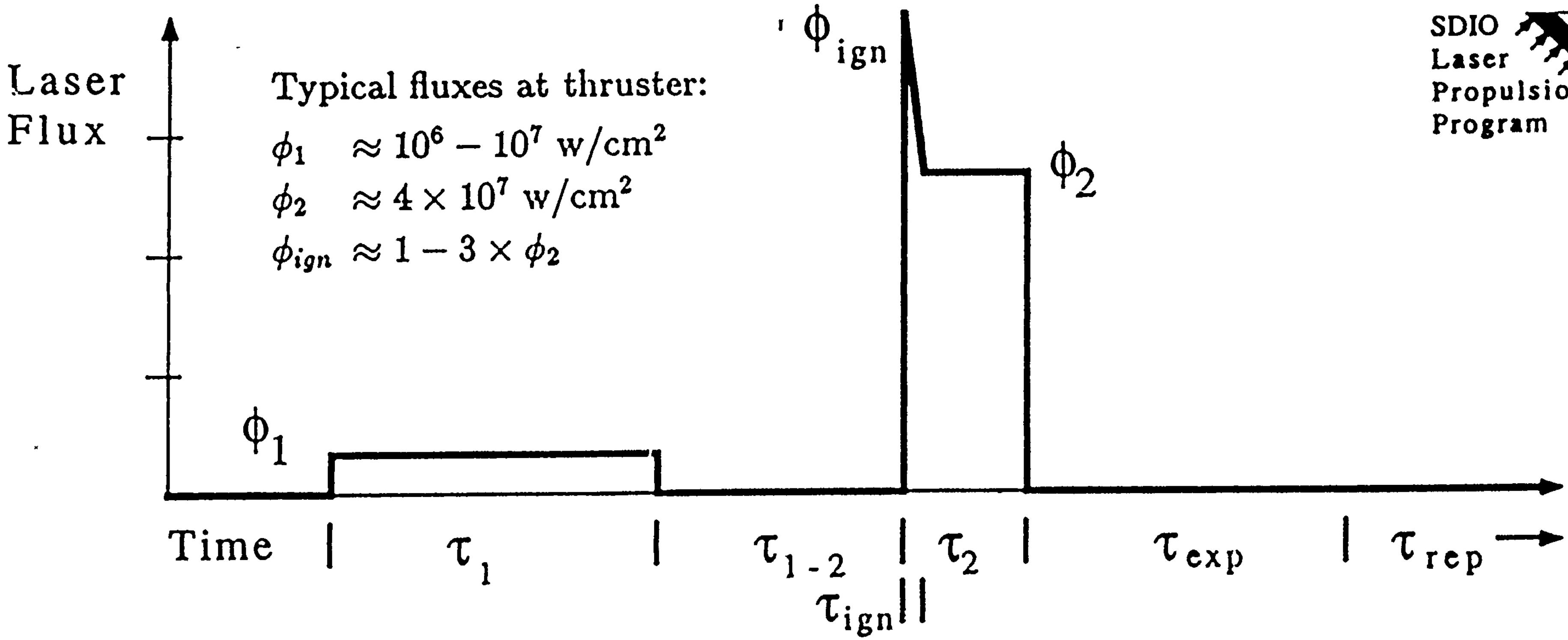
$$I_{sp} = 800 \text{ sec} \Rightarrow v_{exh} = 8 \text{ km/sec} \Rightarrow 1/2 < v_{exh} >^2 = 32 \text{ kJ/g}$$

- Energy Losses:
  - Heat of vaporization
    - Up to 23 kJ/g (Li), worse if propellant isn't "black"
  - Radiation
  - Internal kinetic energy ($< v^2 > - < v >^2$) of exhaust
  - Broken molecular bonds ("frozen flow")
    - Nonequilibrium chemistry at 2000 - 10,000 K
    - Reaction rates unknown for most species
- "Dribbling" Losses: Evaporation of propellant or structural mass at low T, V
  - By leakage through LSD wave
    - Initiation takes several nanoseconds
    - Nonuniform beam may have holes
  - By radiation or conduction from hot gas.
  - Main beam evaporates, e.g., propellant reinforcement or sensor struts
    - Payload protected by geometry or by shielding

Beam Parameters for Double-Pulse Laser Propulsion

- $\lambda = 10.6\ \mu m$ (or nearby)
- Average power 10^6 to 10^9 watts
- Peak flux $\phi > 10^7\ w/cm^2$ at vehicle; 100x lower at beam projector
- Pulse length τ = 50-100 ns (FEL), 1-2 μs (CO_2)
  - Double pulse format: Prepulse is $\approx 10\tau$, $\approx 10^{-2}\phi$
- Pulse frequency $f \approx 1$ kHz (FEL), 100 Hz (CO_2)
  - Duty cycle depends on average power, nominally 10^{-4}
- Mirror diameter $D \approx 10$ meters; Vehicle diameter d   1 meter
- Range R goes from <100 km (in atmosphere) to >1000 km (diff. limit)
- Slew rate ≈ 2 milliradians/second

DOUBLE-PULSE THRUSTER -- LASER PULSE SHAPE



τ_1	Evaporation ("metering") pulse, $\approx 1 - 5\ \tau_2$
τ_{1-2}	Interpulse time, $\approx \tau_1$
τ_{ign}	Ignition spike to initiate LSD wave, nominally < 100 ns
τ_2	Main ("heating") pulse, nominally 1 μs
τ_{exp}	1-D expansion time; must be $> 3 - 10\ \tau_2$ for efficient thrust
τ_{rep}	Repetition time (delay until next pulse pair), $>> \tau_{exp}$

PROPELLANT POSSIBILITIES

- What we want:
    - Moderate heat of vaporization (ΔH_{vap})
        - Too high $\rightarrow$low efficiency; Too low $\rightarrow$large dribbling losses
    - Low dissociation energy (ΔH) OR fast recombination
    - Low *mean* mass of products
        - Low exhaust temperature keeps radiation loss low
        - For $v_{exh} \sim 8$ km/sec, no *inherent* benefit to masses below ~ 10
    - Reasonable to handle
        - E.g., solid hydrogen or HF probably poor choices
        - Easy to fabricate with additives for "blackness", easy ionization

- What we've got:
    - Ice — Cheap, easy to handle, most-studied chemistry; Δ H = 17 - 54 kJ/g
    - NaH — Lowest ΔH (6 kJ/g); may ionize too well
        - Other light hydrides possible: AlH_3, $LiAlH_4$, etc. (but not LiH)
    - Li — $\Delta H = \Delta H_{vap} = 23$ kJ/g; hard to make "black".
    - Air — Limited to low v_{exh}, but widely available - at low altitude!

    - Most others too heavy (e.g., Al) or too high ΔH (CH compounds)
    - Inventions needed: doping, composites, "energetic" propellants, etc.

Atmospheric Propagation – Concerns for Laser Propulsion

- Raman – NOT a problem at 10 μm
  - Threshold flux varies as λ^{-1}; $\approx 10^8$ w/cm^2 @ 1 μm
  - LSD ignition flux varies as λ; problems arise below 3 μm
- Particulates - a minor problem
  - Well below threshold at (primary) mirror; no air near vehicle
  - Problem during flight through atmosphere?
- Thermal Blooming – Major problem
  - Absorption by CO_2 – relatively complex
    - Kinetic cooling, bleaching effects
    - Wavelength dependence for off-line (isotopic) laser
  - Absorption by water vapor
- Turbulence
  - Relatively large cell size ($\approx$1 m), but long "throw"
  - We need uniform illumination

CURRENT LASER PROPULSION RESEARCH

- Double-pulse LSD*-wave thruster development
  - 1-D modelling of double-pulse thrusters (NRL, PSI, LLNL)
  - Initial analysis and modelling of 2-D and rep-pulse effects (PSI, Stanford)
  - Small-scale experiments (AERL, PSI, Spectra)
    - Double pulses in vacuum
    - 3 to 75 joule, 100 ns pulses (CO_2 TEA lasers)
    - Impulse and mass loss measurements
- Other Topics
  - Experiment scaling
    - E-beam pumped SCALEUP (AERL)
  - Air-Breathing thrusters (RPI)
  - Trajectories and guidance (LLNL)
  - Acoustics (Stanford)
  - Atmospheric propagation

*Laser Supported Detonation

INITIAL RESULTS - VERY ENCOURAGING

- Spectra Technology—$I_{sp} = 600 - 1300$ s, η up to 19%
  - Polyethylene propellant in vacuum

$$\phi_1 = 2 \times 10^7 \text{ w/cm}^2 \quad \tau_1 = 100 \text{ ns} \quad \tau_{1-2} \sim 100 \text{ ns}$$
$$\phi_2 = 2 \times 10^8 \text{ w/cm}^2 \quad \tau_2 = 100 \text{ ns}$$

- PSI—Significant (2×) enhancement of I_{sp}, η at optimum interpulse time
  - Glass propellant (good ignition properties)
  - $I_{sp} \sim 270$ s, $\eta \sim 8\%$

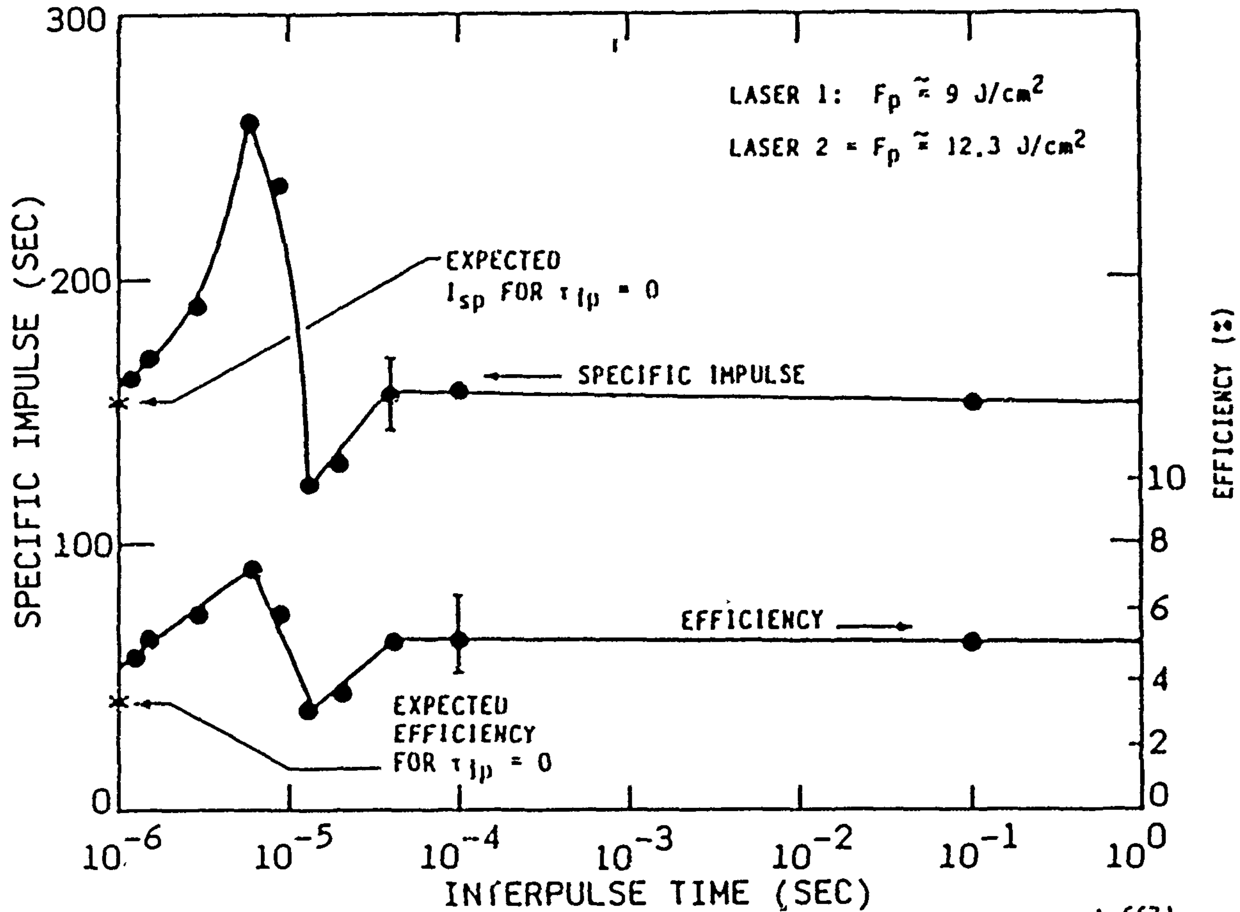
- PSI—Ignition threshold < 2 J/cm^2 on metal flakes

- PSI—$I_{sp} > 600$ s, $\eta \sim 17\%$ with single 12 μs pulse
  - Carbon composite "propellant" (data from lethality tests)
  - Steady state: $>$ 100 pulses at 100 Hz from REP-3 CO_2 laser

- ...And we've barely started!
  - No effort yet to optimize laser pulses or propellant
  - Expect reduced losses with longer pulses, larger spots
  - Design goal is only $I_{sp} = 800$ s $\eta = 40\%$; 600 s and 20% will fly

(η = thruster efficiency $= \frac{1}{2}\dot{m}V_{exh}^2/E_{laser} = \frac{1}{2}V_{exh} \times C.C.$)

SPECIFIC IMPULSE VS. INTERPULSE TIME (GLASS TARGET)



A-6671

WHY LONGER PULSE LENGTHS?

- Reduced ignition losses
  - Ignition takes $\approx$ 10 ns at typical fluxes
  - "Merging" of LSD's from ignition sites takes time
- Longer time for recombination – less frozen flow
- Reduced dribbling due to conduction
  - Thermal diffusion distance varies as $t^{1/2}$
- Closer to ideal LSD-wave behavior
  - Absorption depth is $\approx$ LSD-wave travel at 50 ns
- **BUT** losses to edge effects (2-D expansion) grow rapidly with t
  - Thruster radius must be 10 - 100 times LSD-wave travel
  - Probable optimum: 1 - 2 μs pulse for 1 meter thruster diameter

CENTERLINE MEASUREMENTS
– All the Data for 1/10 the Photons

- Edge effects (rarefaction wave) propagate in at $\frac{1}{2}\,V_d$
  - 0.5 cm/μs for typical LSD wave
  - Center is not "aware" of edge until $t = 2r_{spot}/V_d$
- Therefore, make measurements on central "plug" in larger spot
  - Impulse and mass loss
  - Pressure vs. time
    - Yields informacion about recombination rates
  - Spot size is typically 1/3 that for full 1-D behavior
  - Laser energy is typically **1/10** that for full 1-D behavior

1988 LASER PROPULSION PROGRAM GOALS

- Continue small scale experiments and modelling
  - Explore propellant choices, study ignition
  - Theory and modelling to optimize thruster, support experiments
- Scale experiments to longer pulses and higher energies
  - Two kilojoule experiment program
  - Possible 500 J experiments at U. of Washington
  - Basically settle all single-shot physics issues
    - Real values for full-size thruster I_{sp} and efficiency
- Begin rep-pulse experiments [NOW 1989]
  - ~1000 pulses at ~100 kW average power (100 Hz × 1 kJ)
    - Reach steady-state; demonstrate uniform burning
    - Few $\times 10^4$ pulses needed for full launch-to-orbit burn
  - Settle basic engineering issues for thruster design
  - Demonstrate continuous thrust – fly something significant

MICROWAVE PROPULSION

Dr. Michael M. Micci
Department of Aerospace Engineering
The Pennsylvania State University
University Park, PA

Microwave energy can be absorbed by a gas in one of several modes in order to heat the gas to a high temperature. Because the region of energy deposition can be located away from any material walls, a higher gas temperature can be obtained than in devices which utilize wall heating. Allowing the high temperature gas to expand through a nozzle converts the internal thermal energy to directed kinetic energy to produce thrust. Experimentally measured values for microwave plasma temperatures in a nonflowing gas indicate that specific impulses up to 2000 seconds are possible. There are several advantages for the absorption of microwave energy as compared to laser energy:

1) Microwave energy can be introduced into the absorption chamber through a dielectric window, avoiding the need for an optically transparent window capable of handling high pressures and thermal gradients.
2) Gas absorptivities are higher at microwave wavelengths than at the much shorter laser wavelengths. Thus less power is required to ignite and sustain a microwave plasma compared to a laser plasma.
3) There is less radiative heat loss due to lower microwave plasma temperatures. This heat loss is currently being quantified for plasmas which are between optically thin and optically thick.
4) Since microwave wavelengths are of the same order as the dimensions of the absorption chambers, absorption can occur in a tunable resonant cavity.

5) Microwave power can be generated much more efficiently than laser power, making practical the onboard generation of microwave power and avoiding the problems associated with beam transmission and reception. Also, communication and radar satellites already have a source of microwave energy onboard which may be used for propulsive purposes.

There is an understanding of the process of microwave energy addition to a high pressure gas for some of the available absorption modes but no unified comparison of all the modes in terms of absorption efficiency, maximum temperature, etc. Also there is little knowledge of the coupling of the absorbed energy to the gas dynamics required to obtain propulsive thrust. This research is the first effort to examine and compare free floating filamentary (Tm_{01}) and toroidal (TE_{01}) resonant microwave cavity plasmas and planar propagating plasmas in hydrogen gas as well as the-first examination of the coupling of the energy absorption to the gas dynamics in order to convert internal thermal energy of the gas to directed kinetic energy by means of a nozzle expansion.

Free-floating resonant cavity plasmas in nitrogen gas have been generated for the TM_{01} mode and percent power coupled to the gas has been measured as functions of input microwave power and gas pressure. The nitrogen gas temperature for zero flow velocity was spectroscopically measured to be 4500°K. Experiments have recently been initiated using helium gas.

A numerical model of propagating microwave plasmas in hydrogen, helium and nitrogen has been successfully formulated. The model predicts propagation velocities, maximum gas temperatures, and percent input power absorbed and reflected. The model is currently being modified to include radiation losses. The results of this numerical model will be compared to experimentally measured values as they become available.

MICROWAVE PROPULSION

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DEPARTMENT OF AEROSPACE ENGINEERING
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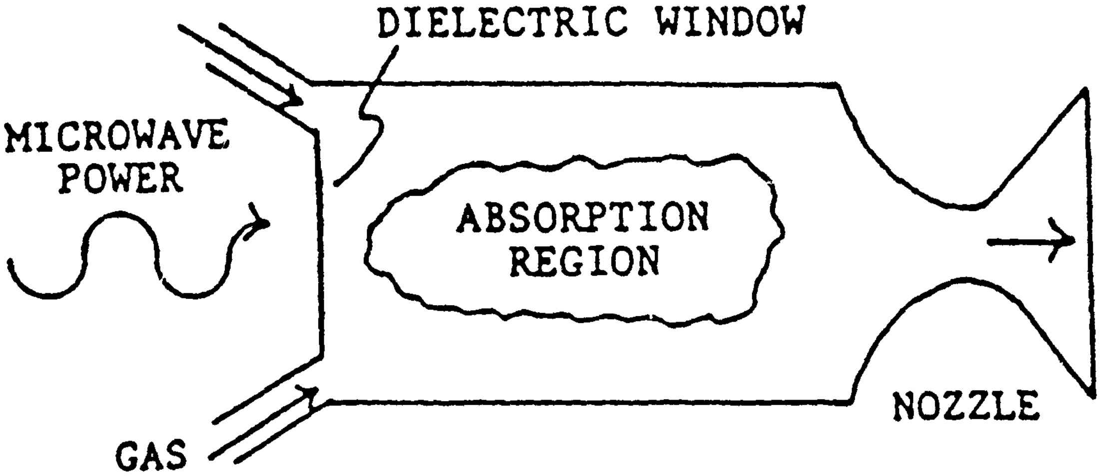
UNIVERSITY PARK, PA

PRESENTED AT THE
AFOSR LASER PROPULSION WORKSHOP
FEBRUARY 8-10, 1988
UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN



SCHEMATIC OF MICROWAVE HEATED THRUSTER

$$U_e = \sqrt{2(h_o - h_e)}$$

ADVANTAGES OF MICROWAVES OVER LASERS

LESS POWER NEEDED TO IGNITE AND SUSTAIN A PLASMA.

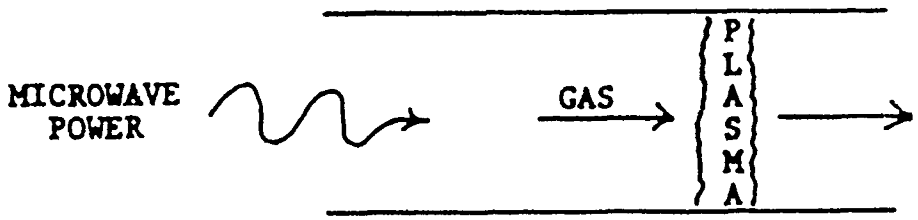
LESS RADIATIVE HEAT LOSS DUE TO LOWER TEMPERATURE.

$\lambda \approx L$, ENERGY ADDITION IN RESONANT CAVITY.

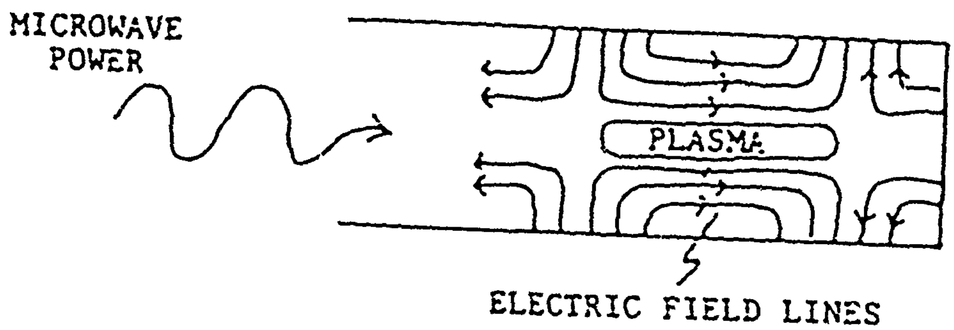
HIGHER GENERATION EFFICIENCIES.

A) ONBOARD GENERATION PRACTICAL.

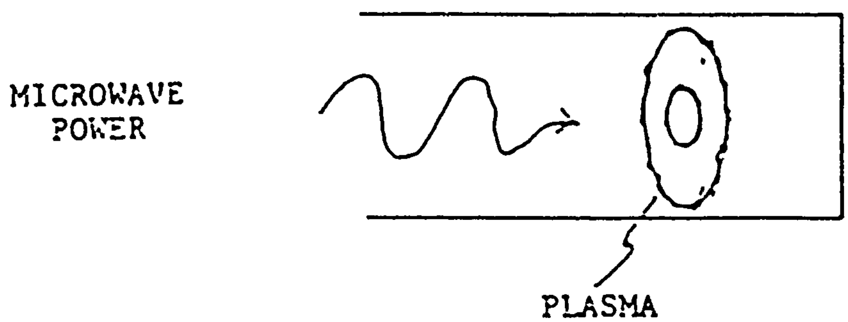
B) RADAR AND COMMUNICATION TRANSMITTERS CAN PROVIDE POWER.



PLANAR MICROWAVE ABSORBING PLASMA PROPAGATING TOWARD ENERGY SOURCE.



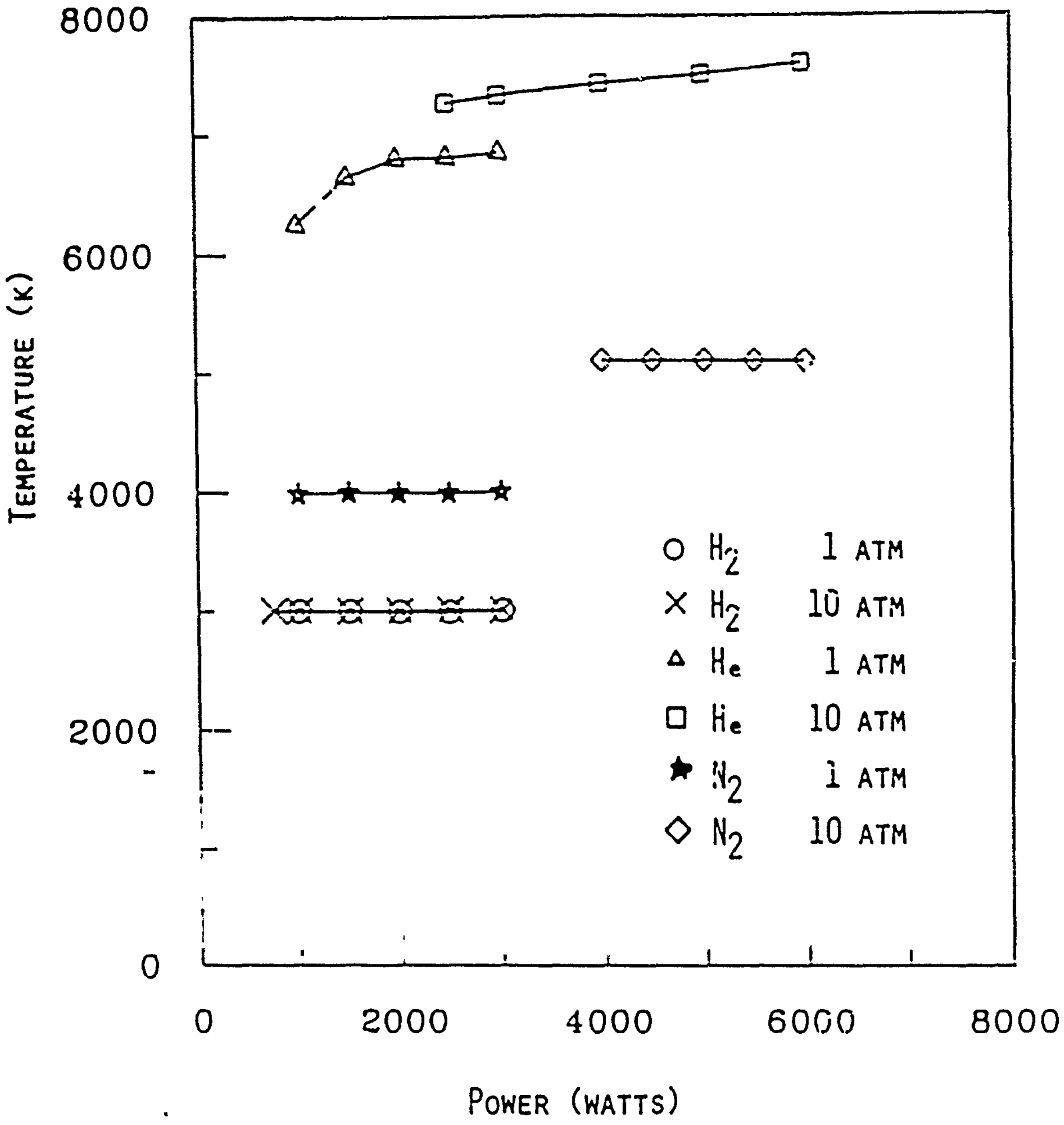
FREE FLOATING TM_{01} FILAMENTARY MODE PLASMA



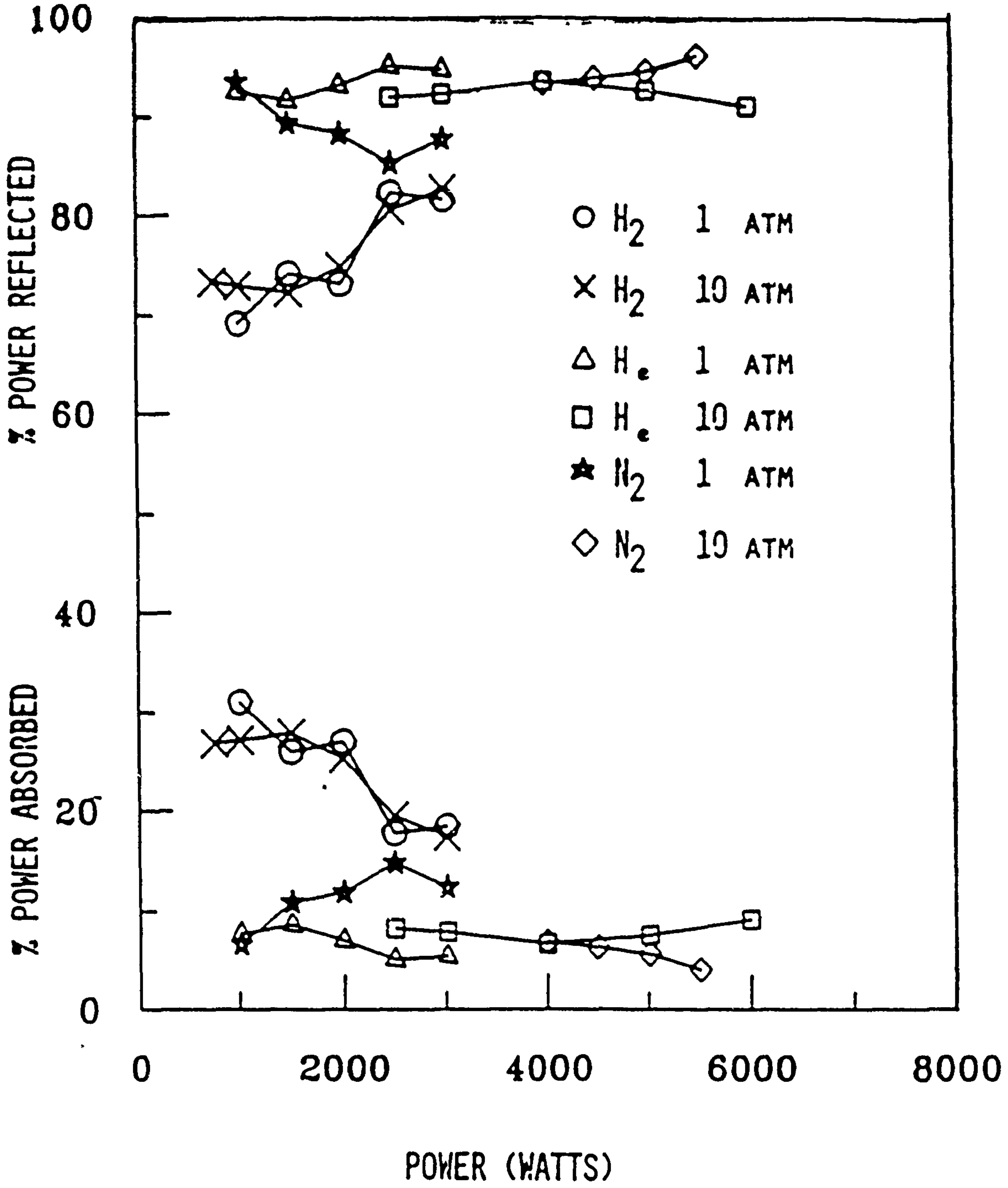
FREE FLOATING TE_{01} TOROIDAL MODE PLASMA

MODE	RESEARCHER	GAS	MAXIMUM TEMPERATURE, K
COAXIAL	BATENIN ET AL.[11]	H_2	8500
	BATENIN ET AL.[12,13]	He	6500
	MIYAKE ET AL.[14]	N_2	6500
PLANAR	BALTIN ET AL.[8]	N_2	6500
	BALTIN ET AL.	Ar	4500
	BATENIN ET AL.[20]	He	11000
TM_{01}	KAPITZA[21]	H_2	7000
	ARATA ET AL.[9]	N_2	6800
	ARATA ET AL.[10]	H_2	9000
	MSU[7]	Ar	1400
	PENN STATE	N_2	4500
TE_{01}	MORIARTY & BROWN[29]	He Ar	

SUMMARY OF EXPERIMENTALLY MEASURED GAS TEMPERATURES



MAXIMUM MICROWAVE HEATED PLASMA TEMPERATURE VERSUS INPUT POWER FOR HYDROGEN, HELIUM AND NITROGEN SHOWING TEMPERATURE DIFFERENCES BETWEEN GASES BUT SMALL INCREASE IN TEMPERATURE WITH INCREASED POWER.



PERCENT INCIDENT POWER ABSORBED AND REFLECTED AS A FUNCTION OF INPUT POWER FOR HYDROGEN, HELIUM AND NITROGEN.

EFFICIENT IGNITION OF PLASMAS BY RESONANT UV LASER MULTIPHOTON EXCITATION

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A new phenomenon has recently been observed in our laboratory in which the threshold for laser plasma formation has been lowered significantly in terms of the incident laser energy (ILE) that is required for plasma formation from a pulsed laser.[1] This phenomenon is based on uv laser resonant multiphoton excitation of atoms as well as small molecules resulting in the efficient production of free electrons in the laser focal volume. We have used excimer lasers, e.g. ArF (193 nm), as well as a tunable Nd:YAG/dye laser system operating in the high uv range (200-250 nm) to demonstrate this effect. The former laser was used to ionize O_2 directly as well as photofragment species from simple hydrocarbons like C_2H_2. The latter laser was used to ionize O_2 and N_2O photofragments (i.e. O atoms) at 226 nm as well as H_2 photofragments (i.e. H atoms) at 243 nm. All of our results to date have indicated that most, if not all, small gas phase fuel or oxidizer molecules can readily release free electrons through efficient multiphoton excitation schemes using a uv laser as long as appropriate resonances have been identified in advance. Unfortunately, resonant multiphoton ionization is still a field in its infancy. Besides lower values of ILE that are required for plasma formation, uv laser resonant plasma ignition has an additional advantage over non-resonant approaches since the plasmas that are generated can be controlled to a much higher degree in terms of plasma energy, especially in the low energy end. This means that particularly strong laser driven detonation waves that may be very detrimental to the structural integrity of the plasma engine can be avoided.

Figure 1 shows the pertinent energy level diagram for oxygen atom electronic excitation. Shown is a two-photon resonance at 226 nm in which the absorption of a third photon from the excited states leads to ionization. Typical laser linewidths (1-2 cm^{-1}) cannot resolve the upper states but clearly resolve the three ground electronic spin-orbit states. Figure 3 shows a strong wavelength dependence in the amount of ILE required for ignition of a premixed flow of H_2/O_2. This same spectral dependence has been observed for plasma formation in a flow of room temperature O_2 only. The wavelengths of the three minima (Fig. 3) correspond exactly to the peaks in the two-photon excitation of oxygen atoms (Fig. 1). This implies that plasma formation is a function of the ease of creating free electrons in the focal volume. Figure 2 dramatically illustrates the difference in ILE values necessary for plasma formation (since a laser spark is necessary to ignite the reactive gases), using the resonance (226 nm) and non-resonance (532 nm) approaches.

In order to ascertain the utility of this uv laser resonance plasma ignition approach to laser propulsion applications, much work still needs to be done. For example, the effect of pressure needs to be explored (all of our work has been done at atmospheric pressure). Also, the use of low ionization additives so that longer wavelength lasers could be used needs to be studied.

This work has been supported by the Air Breathing Combustion Program of the AFOSR Directorate of Aerospace Sciences.

1. B.E. Forch and A.W. Miziolek, Comb. Sci. and Tech., 52, 151 (1987).

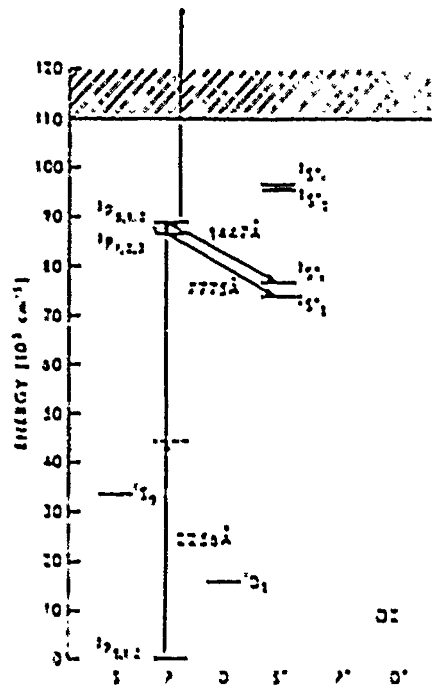


Fig. 1 Partial Energy Level Diagram for O Atoms

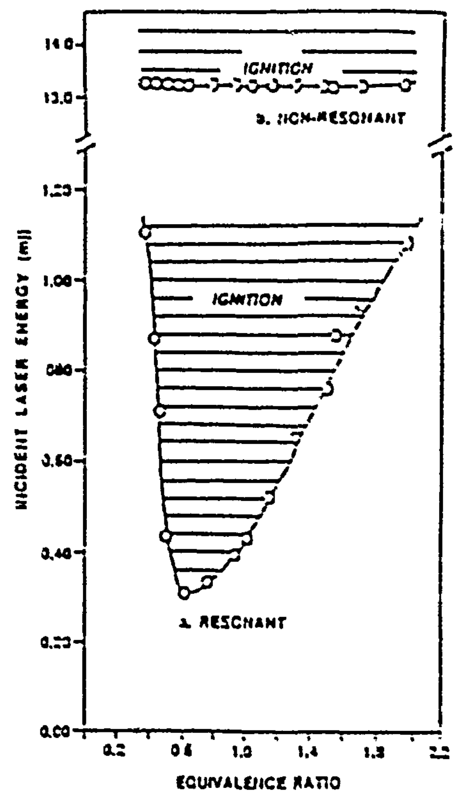


Fig. 2 Laser Ignition of H_2/O_2 Premixed Flows. a) 225.6 nm, b) 532 nm.

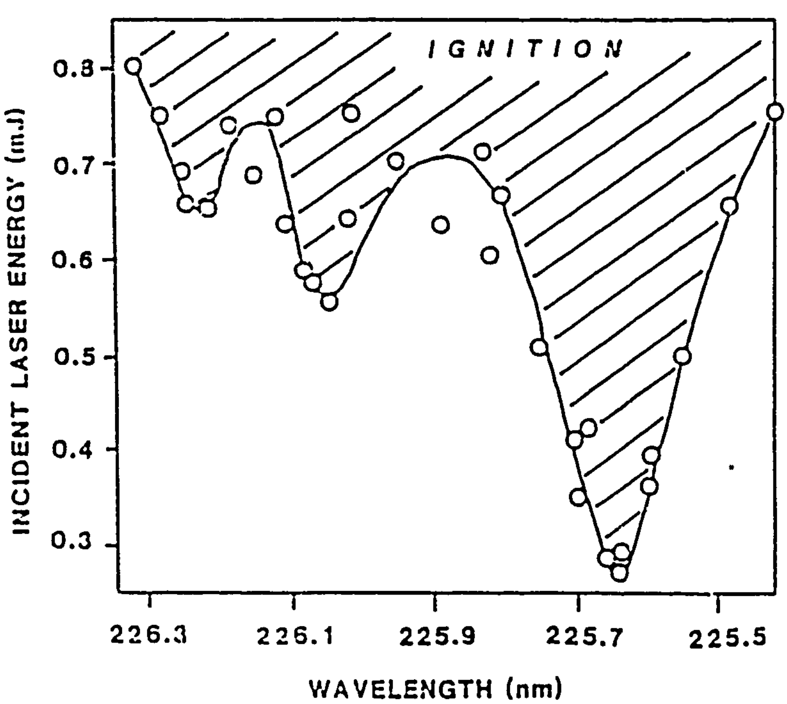
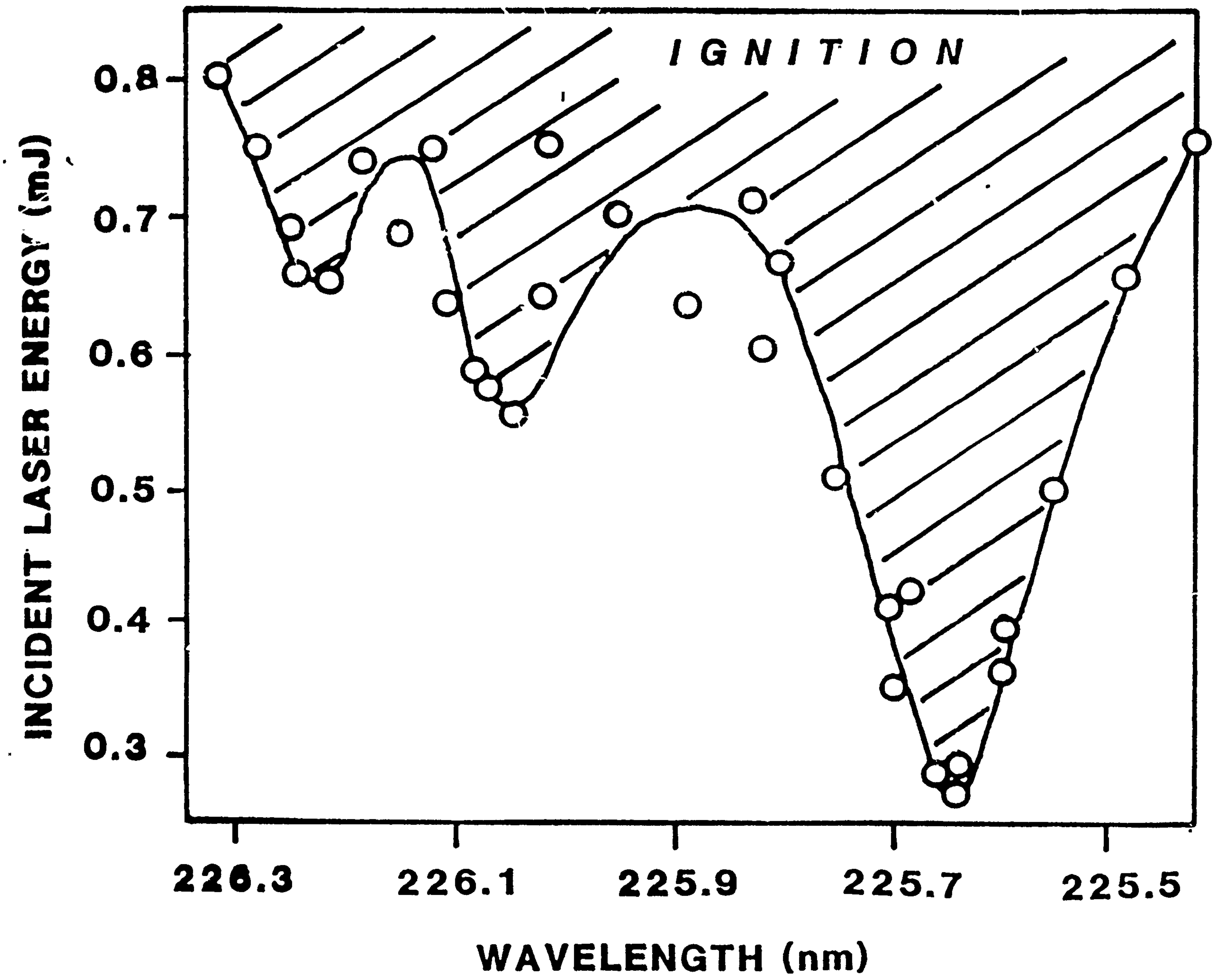
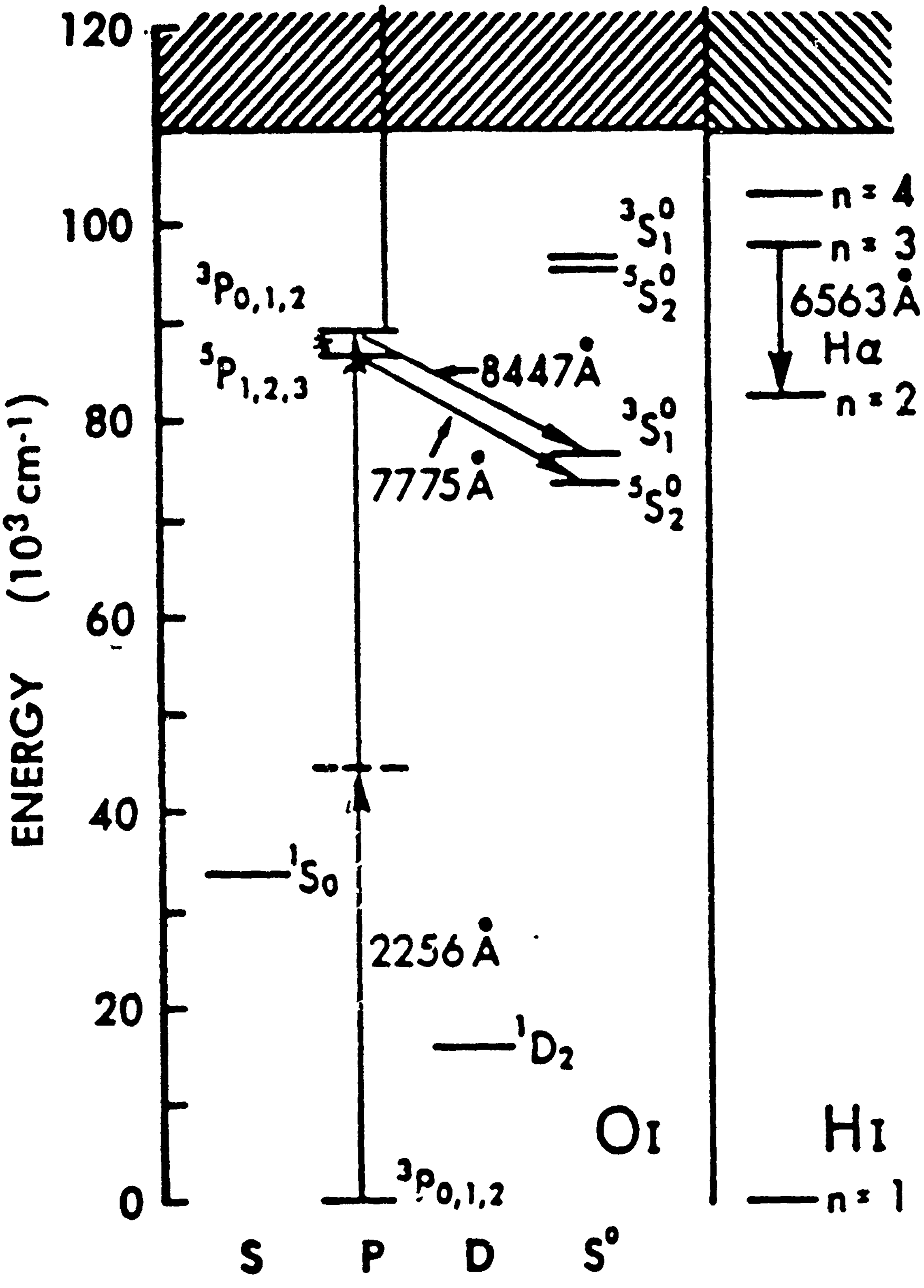


Fig. 3 Laser Ignition of H_2/O_2 Premixed Flows at R.T.

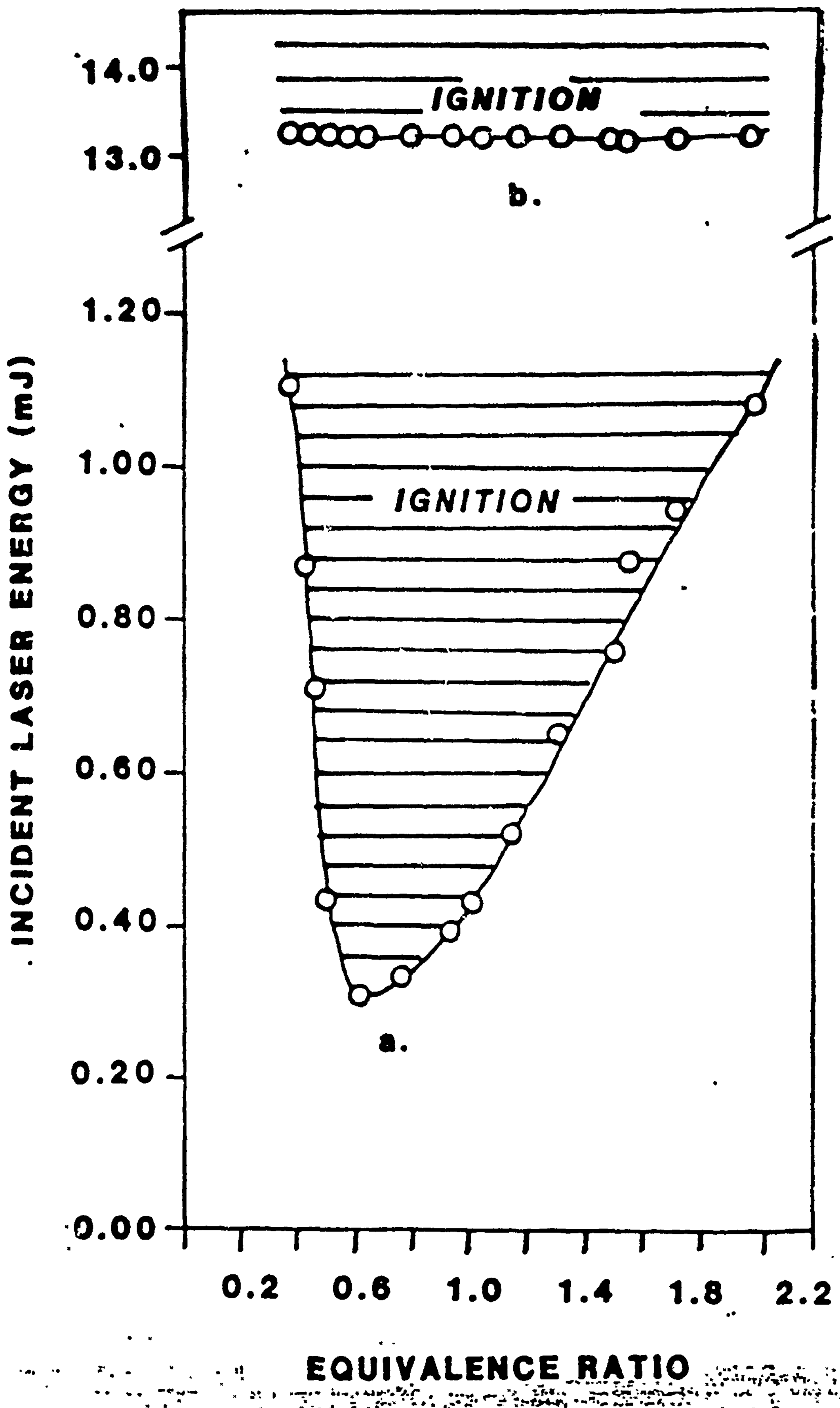
Comb. Sci. + Tech., 52, 151 (1987)

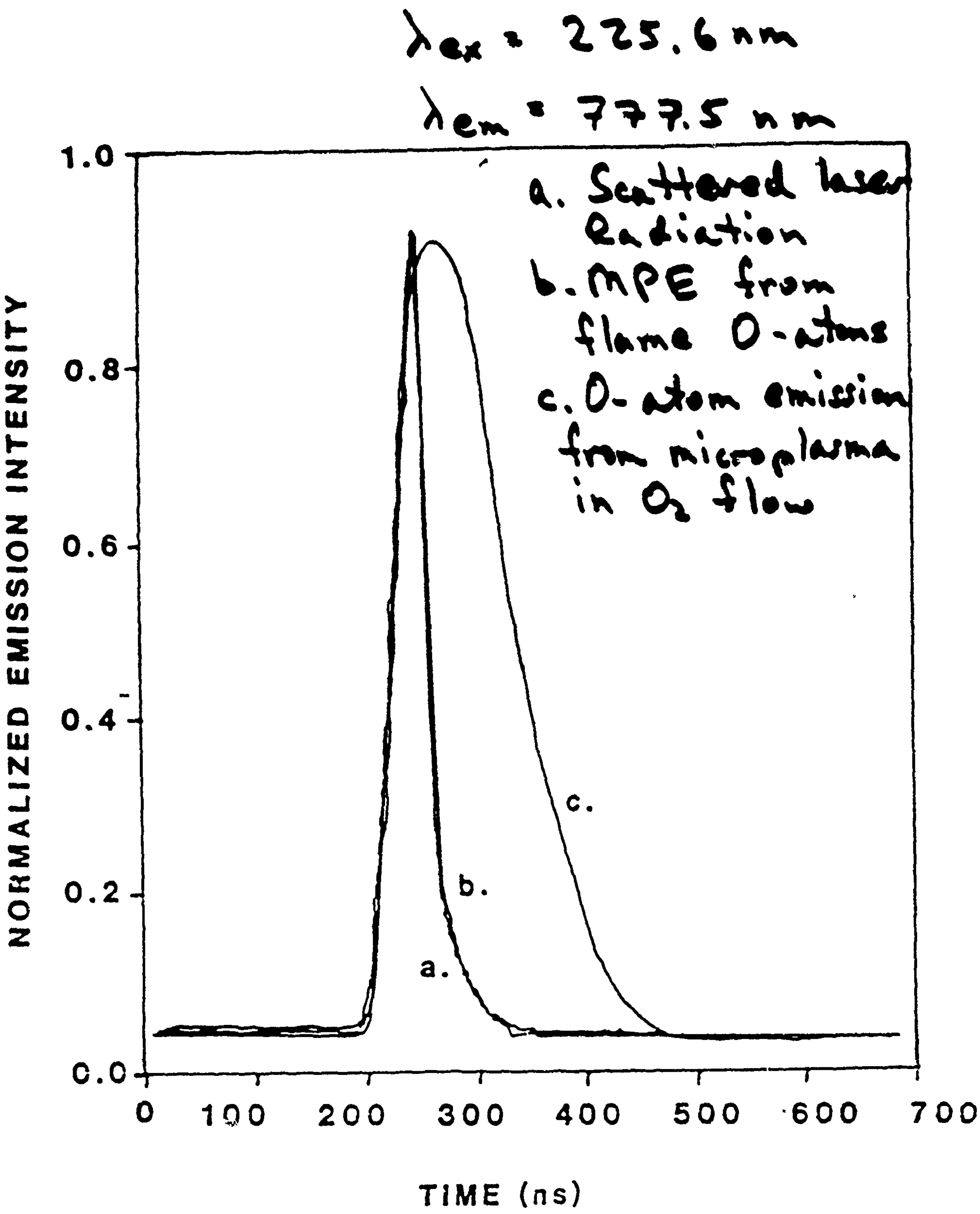




120
100
80
60
40
20
0
ENERGY (10^3 cm^{-1})
$^3P_{0,1,2}$
$^5P_{1,2,3}$
$^3S_1^0$
$^5S_2^0$
8447 Å
7775 Å
$^1S_0$
2256 Å
$^1D_2$
$^3P_{0,1,2}$
O I
H I
n = 4
n = 3
6563 Å
Hα
n = 2
n = 1
S
P
D
S°

ArF 12 mJ No Ig
KrF 12 mJ No Ig
} Stable Resonator





λex = 225.6 nm
λem = 777.5 nm
a. Scattered laser Radiation
b. MPE from flame O-atoms
c. O-atom emission from microplasma in O2 flow
NORMALIZED EMISSION INTENSITY
1.0
0.8
0.6
0.4
0.2
0.0
a.
b.
c.
0
100
200
300
400
500
600
700
TIME (ns)

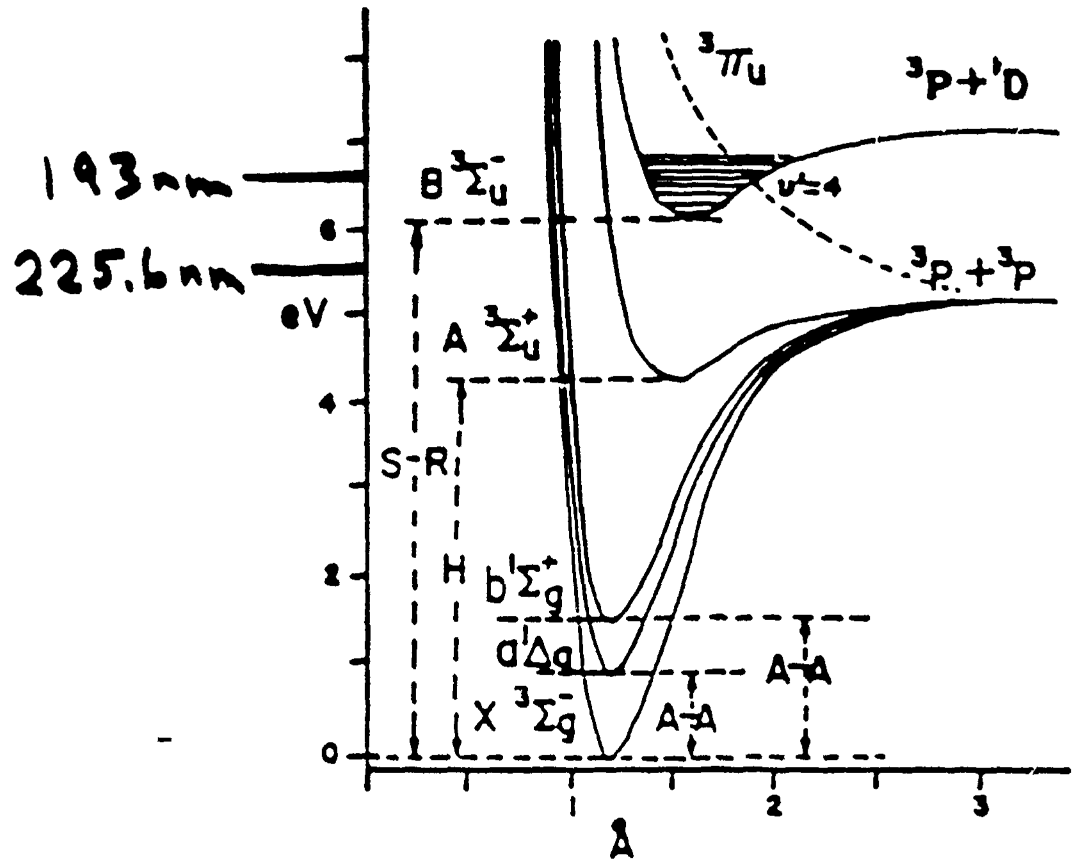


Fig. V-14. Potential energy curves of O_2. S-R, Schumann-Runge bands; H, Herzberg bands; A-A, atmospheric bands. The line-broadening was observed at $v' = 4$ of the $B^3\Sigma_u^-$ state at which point the repulsive $^3\Pi_u$ state crosses the $B^3\Sigma_u^-$ state. See Murrell and Taylor (726). From "Dissociation Energies and the Spectra of Diatomic Molecules" by Gaydon, 3rd Ed. 1968, p. 74. reprinted by permission of Associated Book Publishers Ltd.

from "Photochemistry of Small Molecules", H. Okabe, Wiley-Interscience, 1978.

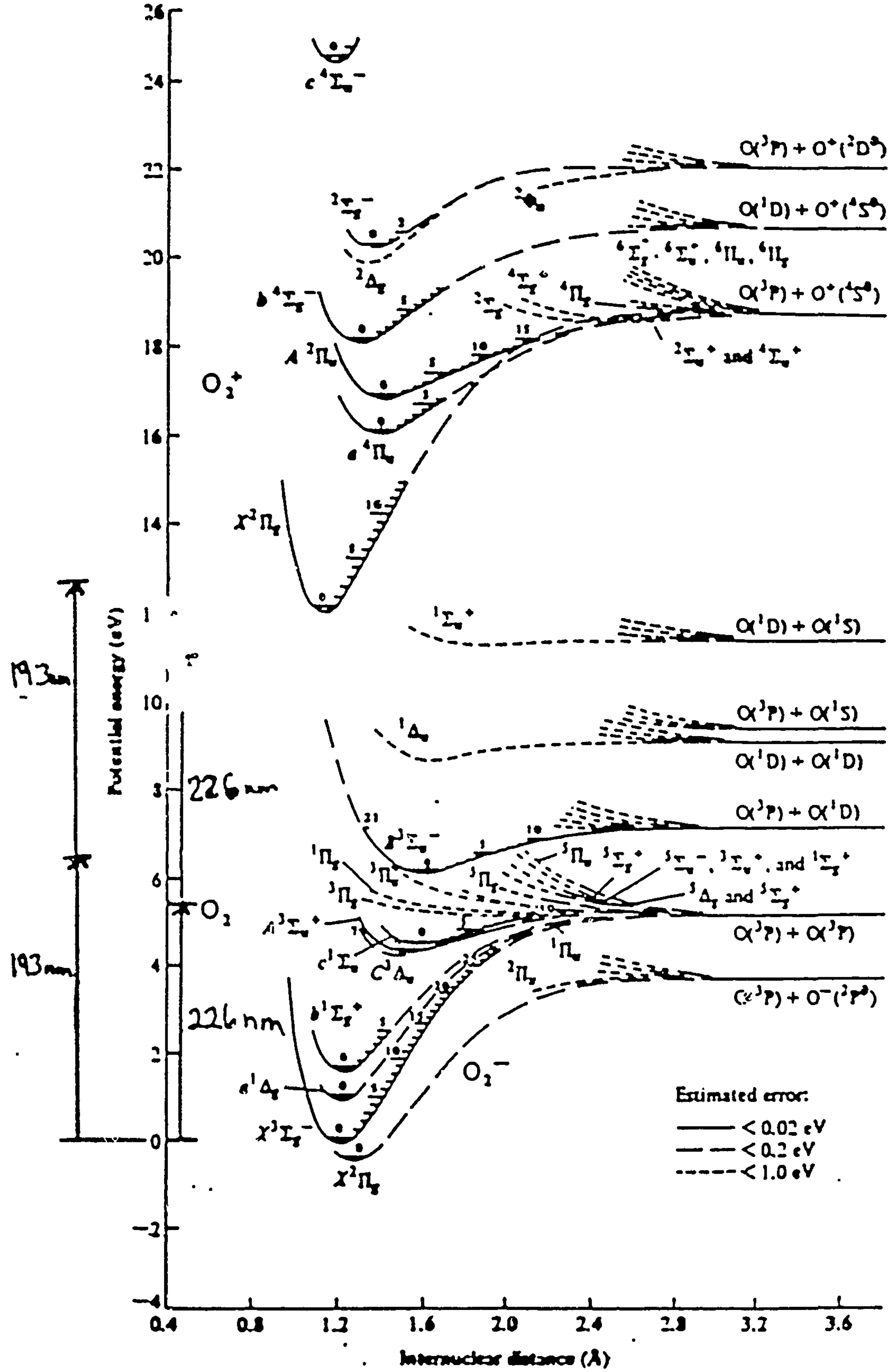


Figure 3.10 Potential energy diagram for O_2 compiled by F. R. Gilmore (Reference 7). [Reproduced with permission of F. R. Gilmore, The Rand Corporation.]

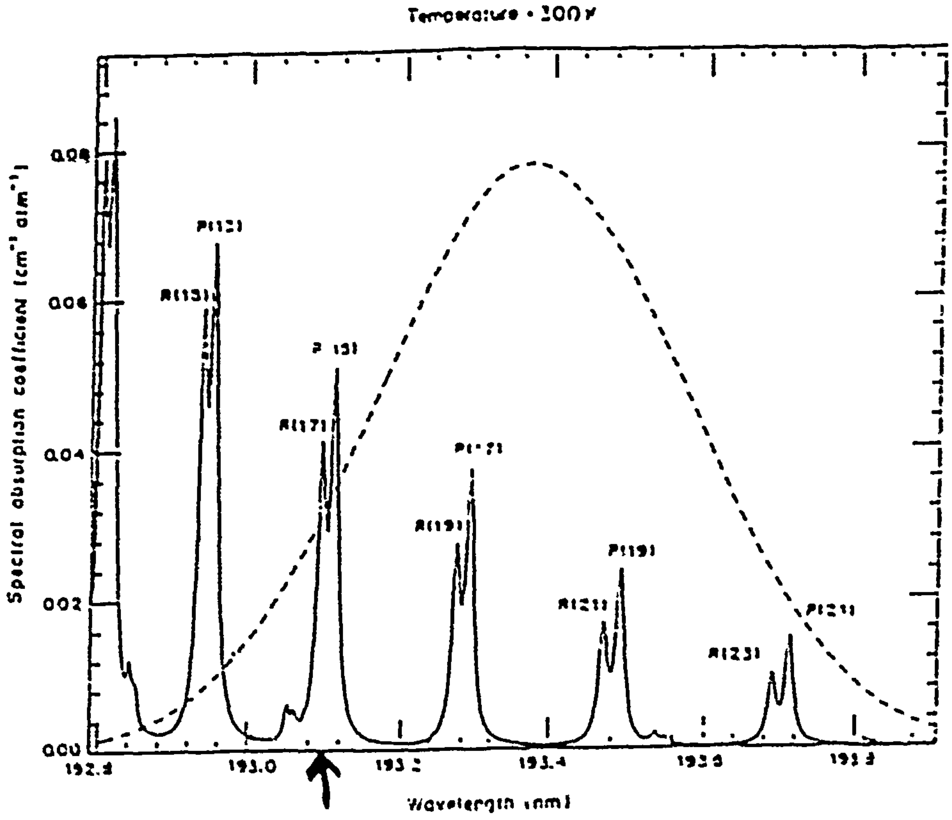


Fig. 2(a)

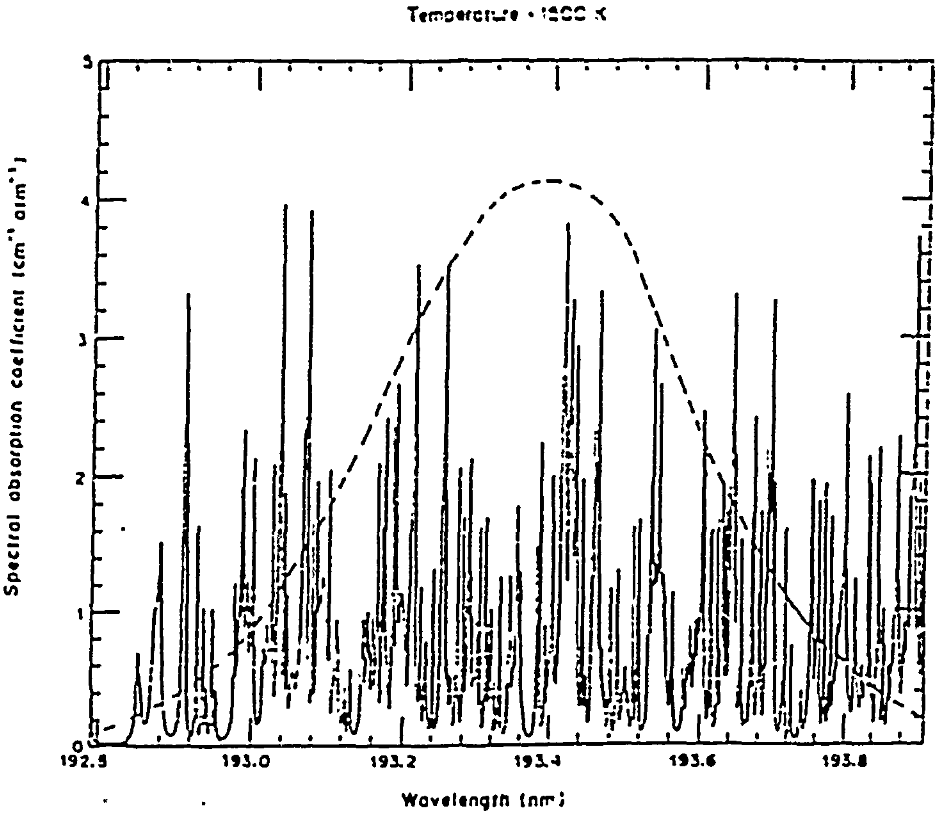


Fig. 2(d)

M.P. Lee and R.K. Hanson, JQSRT, 36, 425 (1986)

J. Chem. Phys 87, 3949 (1987).

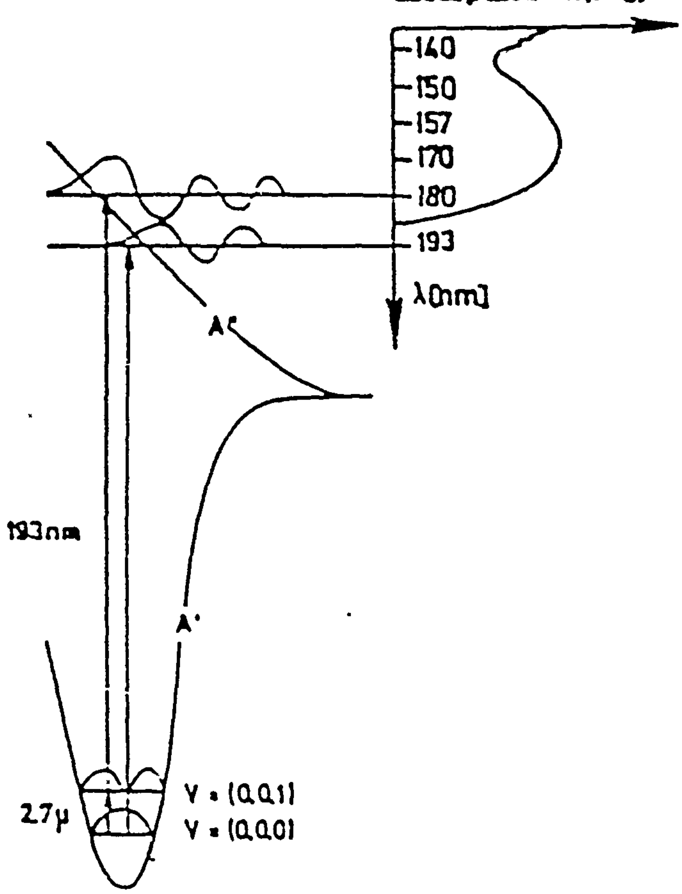
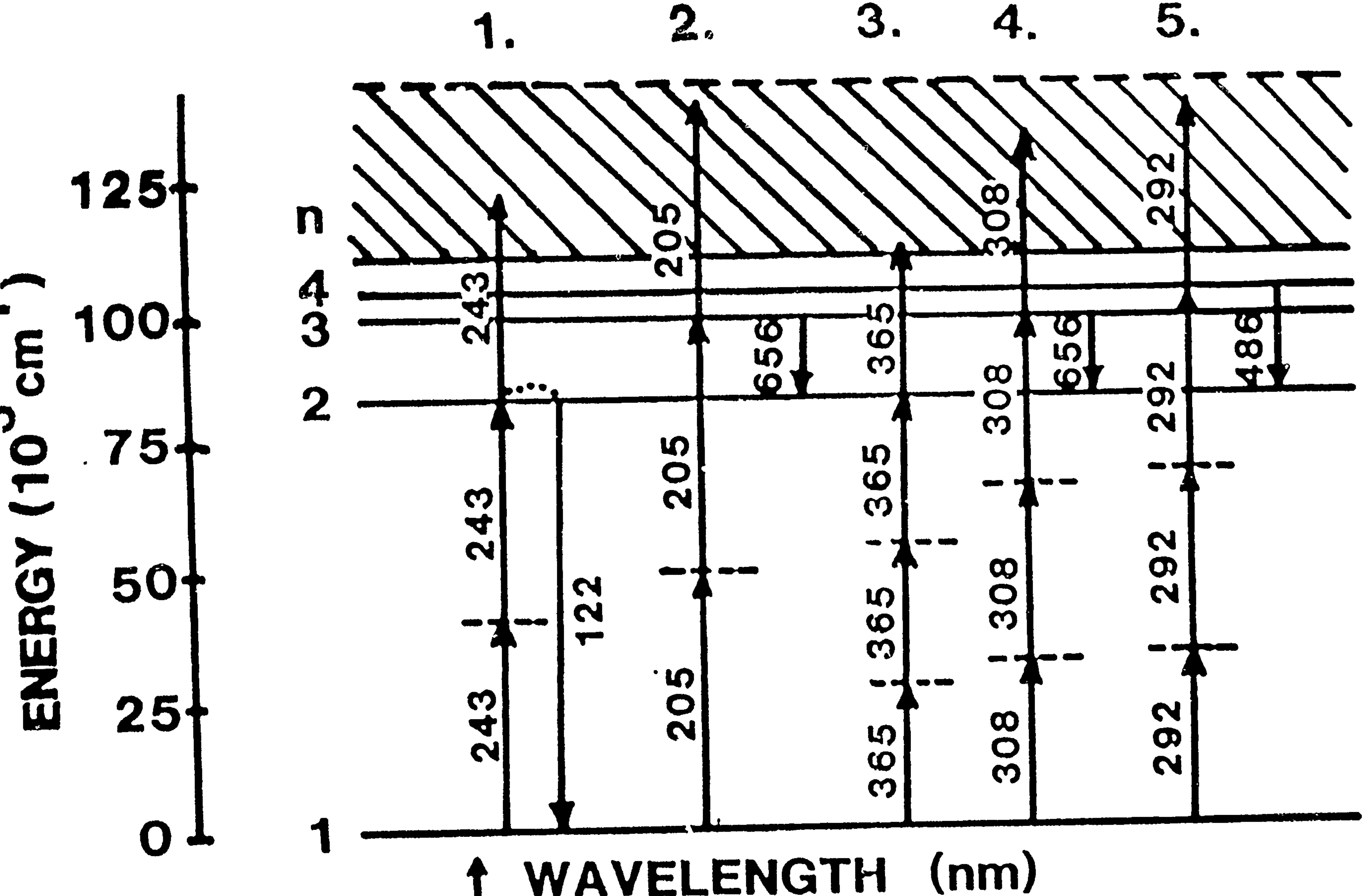


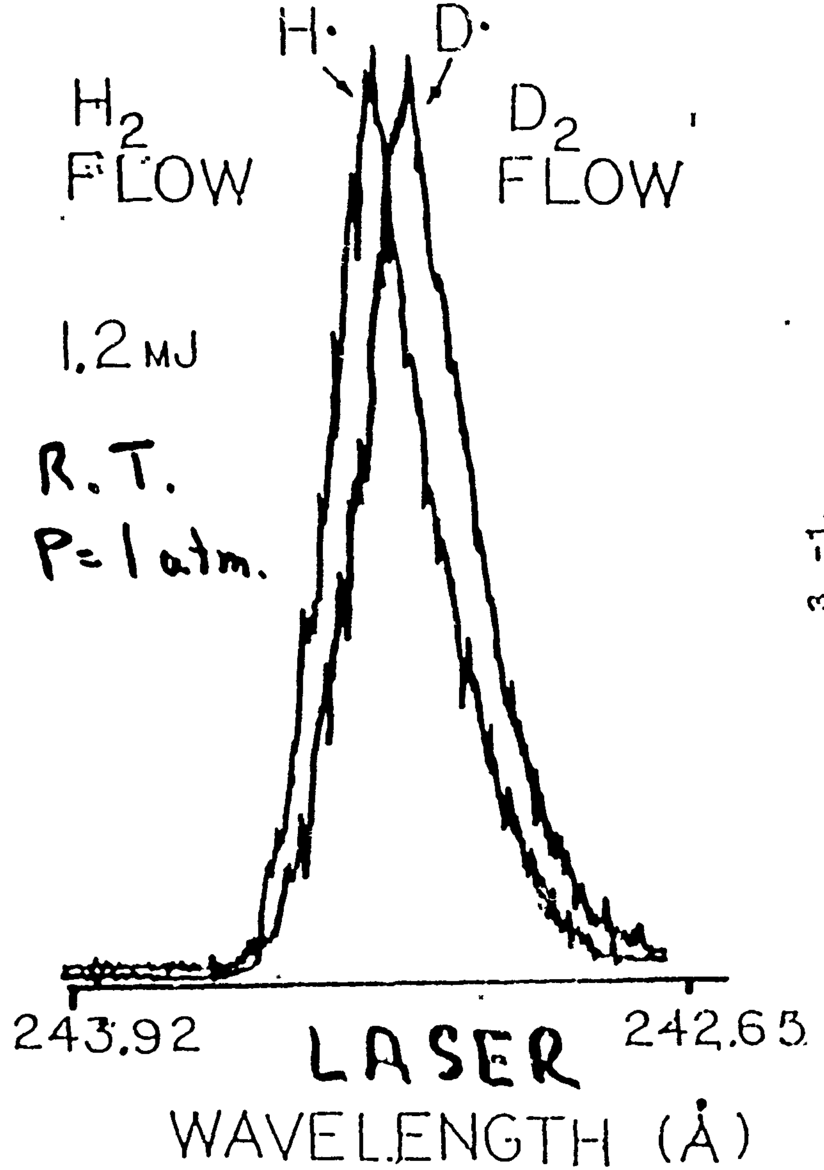
FIG. 2. Idea of the experiment. For the electronic ground state of H_2O the nuclear wave functions are shown for the vibrational ground and excited state. The 2.7 μ correspond to the IR excitation in the experiment. From the vibrational gound state a lower energy is reached after excitation with the 193 nm light than from the vibrationally excited state. The scattering wave function is shown for both cases. At the right side the absorption of H_2O in the first band in the VUV is shown.

H-Atoms

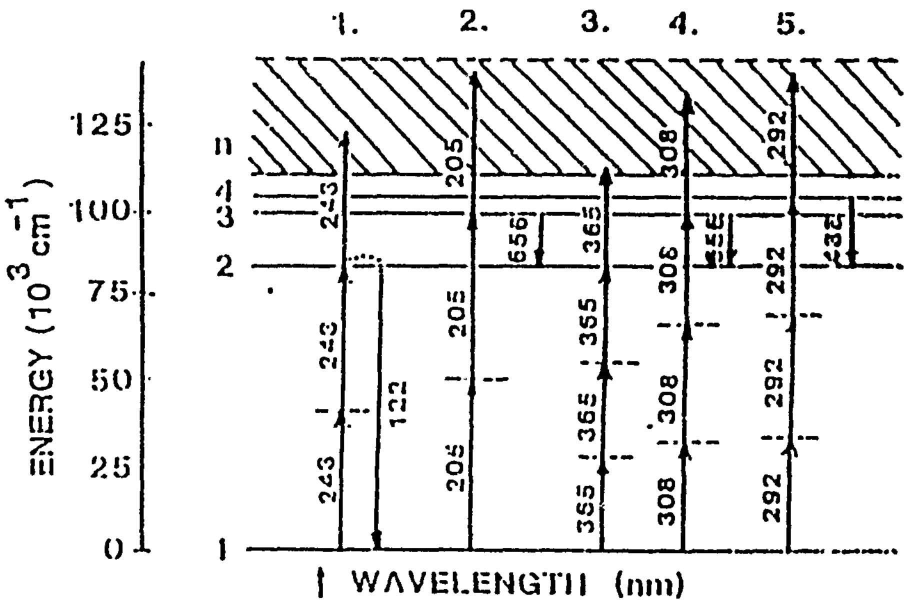
Flame	–	–	–	N	Y
Res. Ignition	Y	–	N	N	N



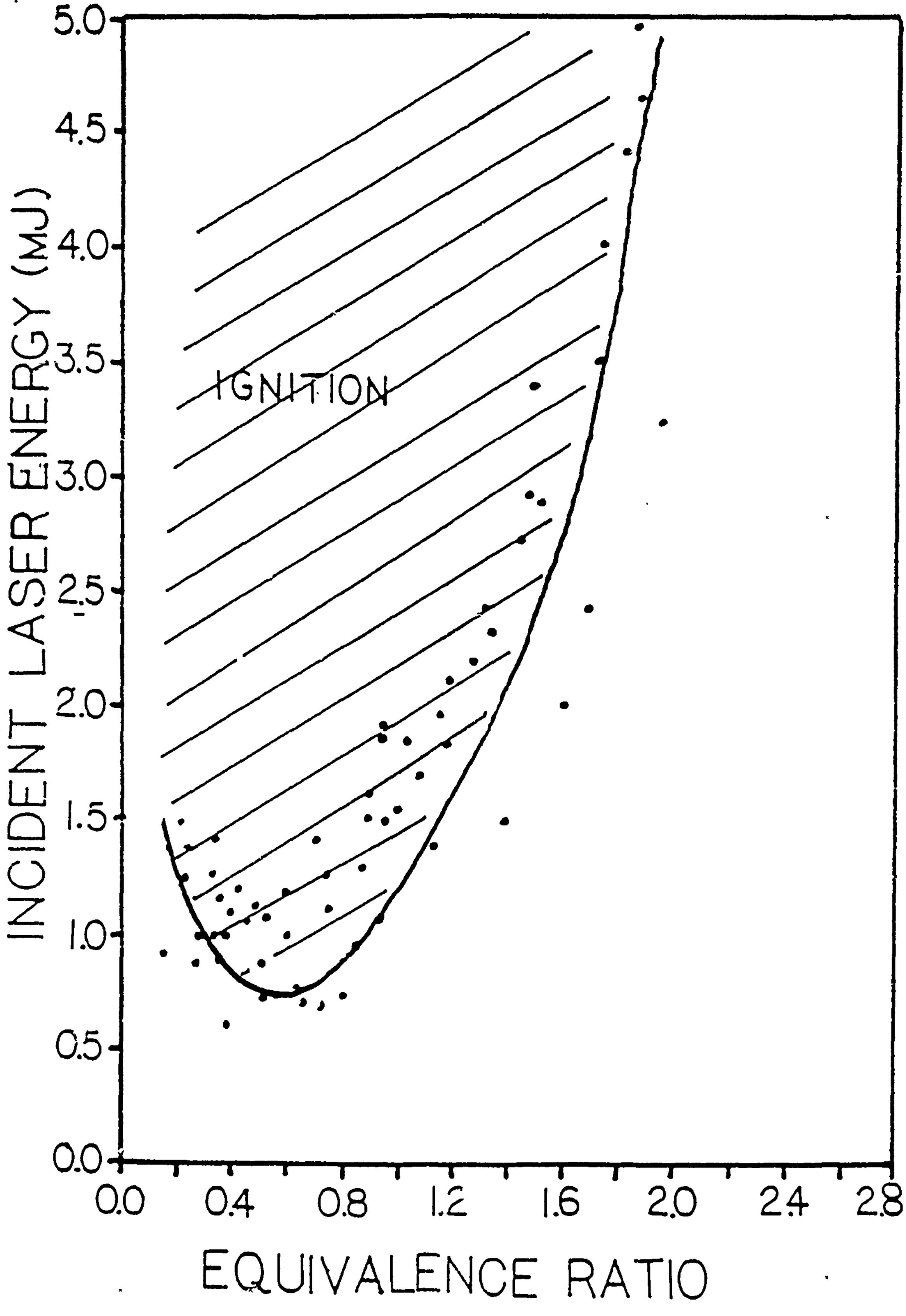
Microplasma Emission $\lambda_{em} = 656$ nm



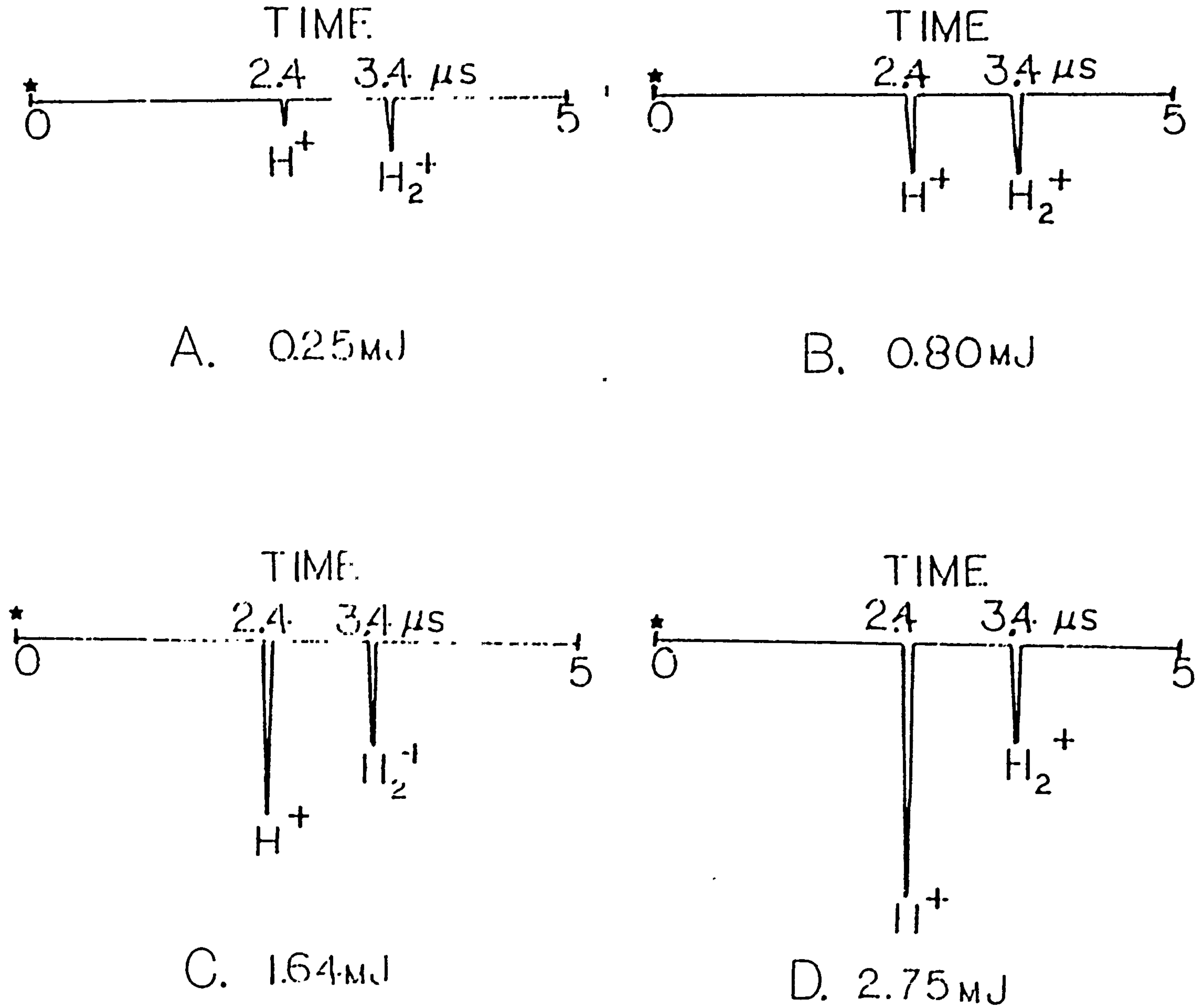
ISOTOPE SHIFT
OBSERVED (24 cm^{-1})
CALCULATED (22.4 cm^{-1})
BLUE

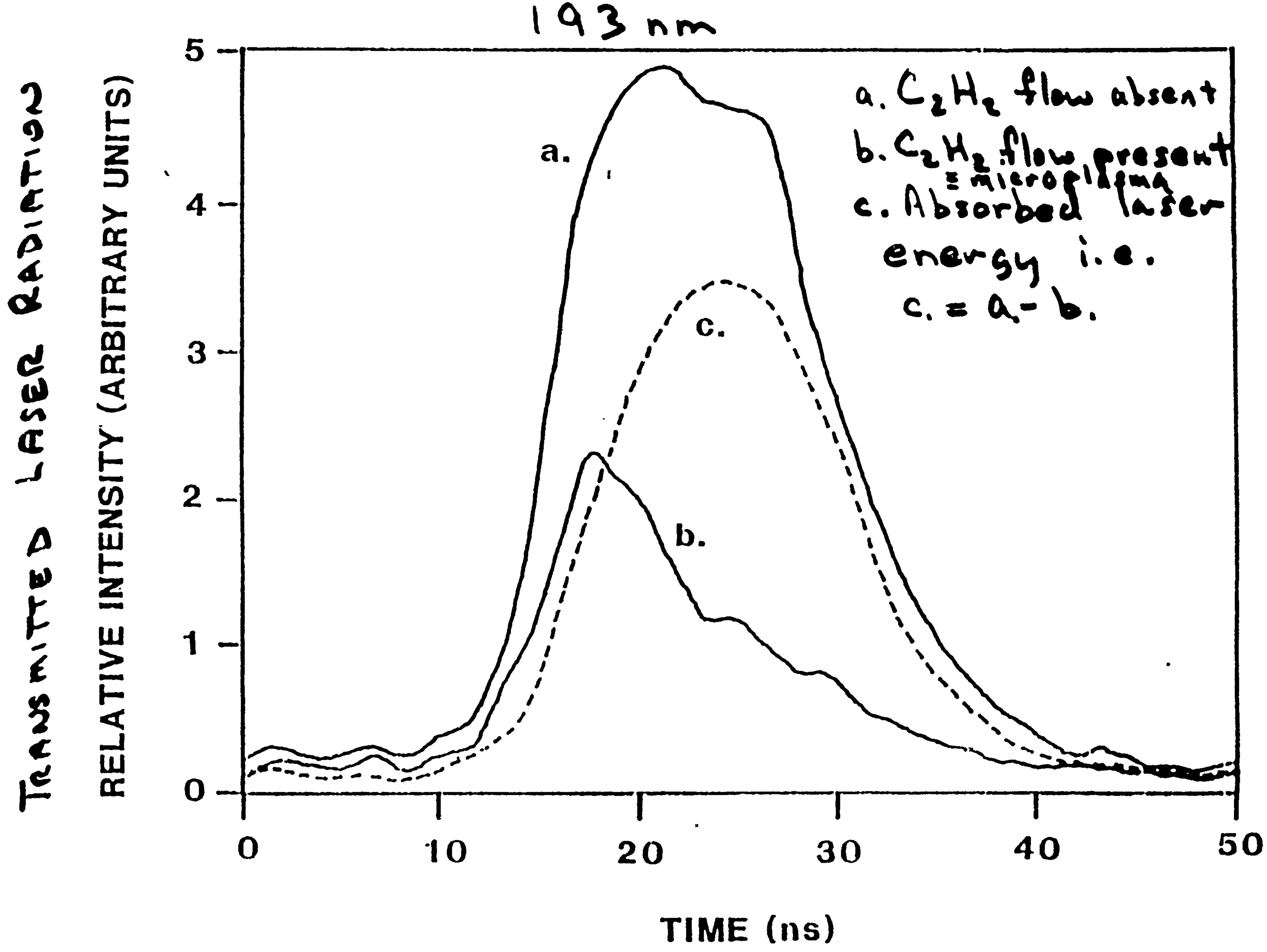


H_2/O_2 Premixed Flows
ArF Eximer Laser (unstable resonator
193nm



Molecular Beam of H_2, Time-of-Flight Mass Spec
ArF Excimer Laser (193 nm)





193 nm
TRANSMITTED LASER RADIATION
RELATIVE INTENSITY (ARBITRARY UNITS)
TIME (ns)
a. C_2H_2 flow absent
b. C_2H_2 flow present
≡ microplasma
c. Absorbed laser energy i.e.
c. = a.- b.
a.
b.
c.
0
1
2
3
4
5
0
10
20
30
40
50

SECTION C

LASER PROPULSION WORKSHOP ATTENDANCE LIST

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at Urbana-Champaign

WORKSHOP AGENDA
(Revised 02/05/88)

1. MONDAY - February 08, 1988: [Conference Room 105 M.E. Lab]

1:00 - 1:30	INTRODUCTIONS/MISCELLANEOUS INFORMATION: Dr. Herman Krier and Dr. Mitat Birkan
1:30 - 2:00	Prof. Dennis Keefer: History of AFOSR and Marshall (NASA) Involvement in Laser Propulsion
2:00 - 2:40	Prof. Dennis Keefer: Current Experimental Research, University of Tennessee Space Institute
2:40 - 3:00	BREAK
3:00 - 3:40	Prof. Herman Krier and Prof. Jyoti Mazumder: Current Experimental Research, University of Illinois at Urbana-Champaign
3:40 - 4:00	Dr. David Byers, NASA-Lewis Research Center: NASA Advanced Propulsion Goals
4:00 - 4:30	Dr. Herman Krier: Design of Laser Propulsion Thruster (Combustion Sciences, Inc.) (SDIO funded project)
4:30 - 5:30	DISCUSSION
7:30 - 9:30	DINNER: Jumer's Castle Lodge (Urbana)

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2. TUESDAY - February 09, 1988: [Conference Room 105 M.E.Lab]

8:30 - 9:00	DISCUSSION: Review of Dr. Birkan's Questions
9:00 - 9:20	Prof. Charles Merkle, Pennsylvania State University: Modeling
9:20 - 9:40	Prof. S. M. Jeng, University of Tennessee Space Institute: Modeling
9:40 - 10:00	Prof. Robert Beddini, University or Illinois at Urbana-Champaign: Modeling
10:00 - 10:15	BREAK

[Continued on Page 2]

WORKSHOP AGENDA [Continued]
(Revised 02/05/88)

10:15 - 11:00	Dr. Jordin Kare, Lawrence Livermore Laboratory: Pulsed Laser Propulsion
11:00 - 11:30	Dr. Ja H. Lee, NSAA-Langley: Lasers Available
11:30 - NOON	DISCUSSIONS
12:00 - 1:00	LUNCH - Illini Union; Colonial Room
1:00 - 1:15	Walking Tour - Central Campus (Weather Permitting)
1:15 - 2:00	Laboratory Demonstration: 10 kW CW Laser (Talbot Laboratory)
2:05 - 2:30	Prof. Michael M. Micci Pennsylvania State University
2:30 - 3:00	(To Be Announced)
3:00 - 5:00	DISCUSSION: Research Programs Needs

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3. WEDNESDAY - February 10, 1988: [Conference Room 105 M.E. Lab]

8:30 - Noon	Dr. Mitat Birkan will lead discussions and questions; continuation of previous afternoon's discussions.

Invitees (remaining) will be given transportation to Willard Airport for return flights.